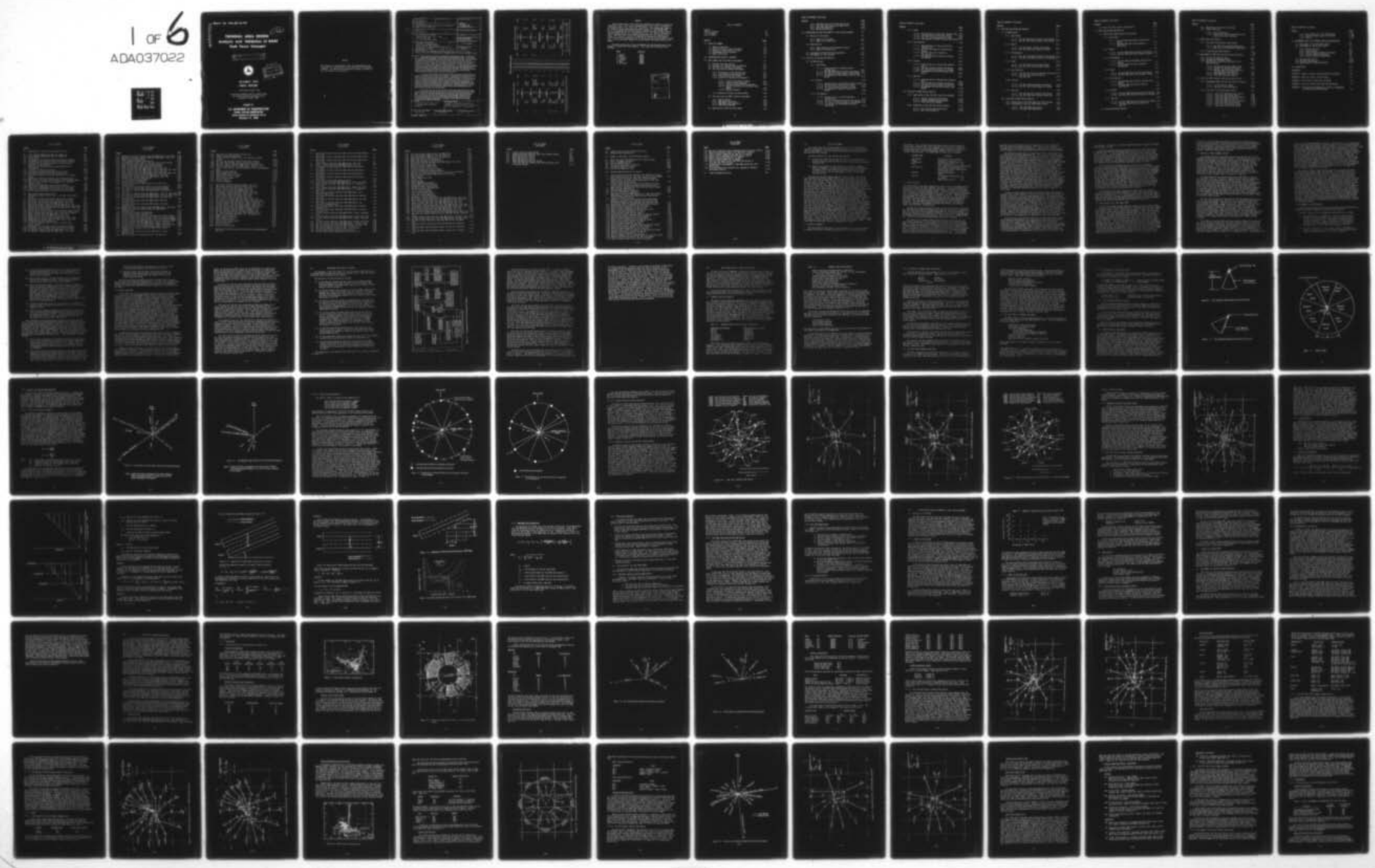
AD-A037 022 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
TERMINAL AREA DESIGN - ANALYSIS AND VALIDATION OF RNAV TASK FOR--ETC(U)
OCT 75 E D MCCONKEY , W H CLARK DOT-FA72WA-3098
UNCLASSIFIED FAA-RD-76-194 NL

1 OF 6
ADA037022



1 OF 6

ADA037022

1.0 1.1 1.25 1.4 1.6 1.8 2.0 2.2 2.5 2.8 3.2 3.6 4.0 4.5 5.0 5.6

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Report No. FAA-RD-76-194

12

B.S.

TERMINAL AREA DESIGN
Analysis and Validation of RNAV Task Force Concepts

OCTOBER 1975

FINAL REPORT

(Published December 1976)

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

NOTICE

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-RD-76-194		

4. Title and Subtitle
TERMINAL AREA DESIGN - Analysis and Validation of RNAV Task Force Concepts

5. Report Date
October 1975

6. Performing Organization Code

7. Author(s)
Edwin D. McConkey
William H. Clark

8. Performing Organization Report No.

9. Performing Organization Name and Address
Systems Control, Inc. (Vt)
1801 Page Mill Road
Palo Alto, California 94304

10. Work Unit No.

11. Contract or Grant No.
DOT-FA72WA-3098

12. Sponsoring Agency Name and Address
Department of Transportation
Federal Aviation Administration
Systems Research and Development Service
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code
ARD-333

15. Supplementary Notes
Report prepared by Champlain Technology Industries, Division of Systems Control, Inc. (Vt.), a subsidiary of Systems Control, Inc., Palo Alto, Calf. 94304

16. Abstract

This document describes the development of Area Navigation (RNAV) terminal area design guidelines for application to medium and high density terminal areas. The design concepts proposed by the FAA/Industry RNAV Task Force were utilized in the development of initial time-phased 2D terminal area designs for Chicago, Denver, Miami, New Orleans, New York, Philadelphia and San Francisco. The time phases correspond to the three time periods postulated by the Task Force: 1972-1977, 1977-1982, and post-1982. The 1972-77 and 1977-82 transition period designs were analyzed in conjunction with a real time simulation to confirm the pilots' and controllers' capability to operate efficiently in a mixed VOR/RNAV environment. The post-1982 designs were subjected to a user economic impact analysis to determine the effects of route length and altitude restrictions on fuel and time. Two 100% fixed gradient VNAV designs were developed for New York and New Orleans using Task Force concepts and were analyzed for their impact on the user and the system.

The initial designs were also reviewed with user groups and with controllers and supervisory personnel at the respective FAA regions. Based on comments received during these reviews, and on the results of the various analyses, a recommended set of terminal area design guidelines was developed and applied to a final set of designs for the seven terminal areas. The guidelines are a modification of the Task Force guidelines which provide for realignment of terminal maneuvering areas and terminal transition areas, consideration of compatibility with present terminal route structures to provide early RNAV benefits, more efficient handling of low altitude routes, and the use of a vertical envelope concept which allows pilot selection of 3D gradients for optimization of aircraft performance. Further modifications of the Task Force guidelines which are required for metroplex areas are described and illustrated in a New York design.

The benefits to both the user and to the ATC system through the use of terminal route structures based upon the recommended guidelines were quantified by additional route length and altitude restriction analyses and by a second real time simulation activity at NAFEC. Benefits for both RNAV and VNAV users were considered. The analyses indicated that route structures based upon the recommended design guidelines produced time and fuel benefits for the user. The simulation results indicated that workload reduction for the controllers and a slight increase in terminal arrival capacity was achieved through the use of RNAV ATC procedures.

410 102

17. Key Words	18. Distribution Statement
Air Navigation, Airspace, Area Navigation, Routes, Vertical Navigation	Document is available to the public through the National Technical Information Service, Springfield, Virgiania 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	542	

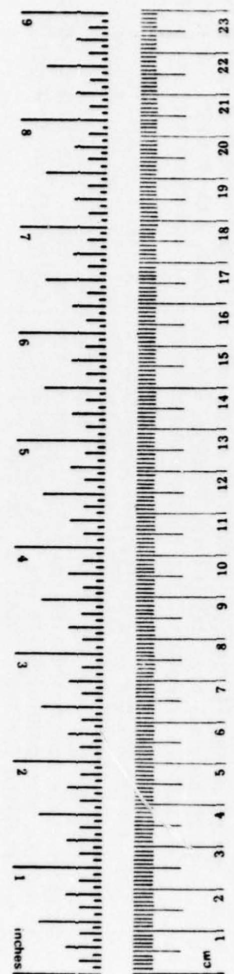
Form DOT F 1700.7 (8-69)

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

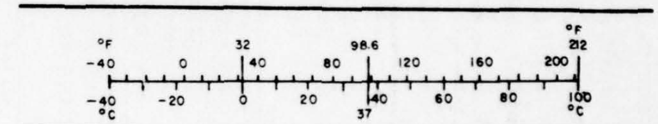
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The work described in this report was performed by Champlain Technology Industries, (CTI), a Division of Systems Control, Inc. (Vt), a subsidiary of Systems Control, Inc., Palo Alto, California. The program was funded by the Federal Aviation Administration under contract no. DOT-FA72WA-3098. Mr. D. M. Brandewie was the FAA Technical Monitor and the Technical Support Program Manager was Mr. D. W. Richardson of CTI. Mr. Edwin D. McConkey, of the CTI technical staff was primarily responsible for the conduct of the study. Mr. William H. Clark, CTI Director of Engineering, contributed sections on vertical separation for 3D offsets and turns and airspace utilization. He also provided suggestions on the content and organization of this report.

The author would also like to aknowledge the contributions made to the project by several FAA staff members. Their names and facilities are as follows:

Name	Facility
R. Cassell	SRDS
J. Maurer	NAFEC
W. Crimbring	NAFEC
F. Woodson	NAFEC
H. Arch	NAFEC
A. Halverson	NAFEC

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF TABLES

LIST OF TABLES
(continued)

1.0 EXECUTIVE SUMMARY

This report describes the development and analysis of RNAV and VNAV terminal area designs, the techniques that were used to create the designs, and the development of a set of terminal area design guidelines based on a modified Task Force concept.

The basic objectives of the program were twofold:

(1) Evaluate the RNAV (2D) and VNAV (3D) Task Force terminal area design concepts by applying them to various medium and high density terminal areas.

(2) Based on an analysis of the terminal area designs, recommend design techniques to be used in the three Task Force time periods defined as 1972-77 and 1977-82 transition periods, and in the post-1982 period, for the development of both 2D and 3D RNAV terminal designs.

The study was divided into two specific design efforts. The initial task consisted of developing RNAV terminal area route structures for the 1972-1977, 1977-1982 and post-1982 time periods for thirteen (13) airports in seven terminal areas. These route structures were based upon Task Force terminal design guidelines. When these initial designs were completed for all three time periods, they were analyzed in order to determine user benefits and the ATC system impact in implementing these route structures. Some apparent weaknesses were observed in some of the route structures for both the user and ATC. As a result a modified set of terminal design guidelines were developed and applied to the New York terminal area. Increased user benefits and more flexibility in the vertical route design characterized the modified New York route structure. At this juncture field controllers at each of the seven terminal facilities were given an opportunity to comment upon the initial design effort and the modified design guidelines. The modified guidelines were endorsed by the controllers as being more desirable than the Task Force guidelines. Comments upon the two design techniques were solicited from airline and general aviation user groups as well. The response from users indicated that increased user benefits as potentially achievable from the modified guidelines were very desirable. As a result of these inputs from controller and user groups, a second terminal route design effort was begun which resulted in post-1982 RNAV route structures for the nine primary airports contained in the same seven terminal areas. These modified terminal route structures were also subjected to user benefit and ATC impact analyses and found to offer increased user benefits with no negative impact on ATC operations. Three of the New York route structures which were developed during the study were used as the basis for real time ATC simulations at NAFEC. These simulations are described in detail in References 13 and 18.

1.1 METHOD OF APPROACH

The study began by selecting a set of fourteen terminal areas for which an extensive data base of present day operations and route structures was

established. These terminal areas consisted of high and medium density airport areas selected from lists contained in the Task Force report [1]. From this initial set of fourteen terminal areas, seven were selected for detailed RNAV route structure development because of their particular terminal characteristics. The seven areas selected were as follows:

Terminal Area	Airports	
New Orleans	New Orleans International	(*)
Denver	Stapleton International	(*)
Philadelphia	Philadelphia International	(*)
Miami	Miami International	(*)
	Fort Lauderdale-Hollywood International	
San Francisco	San Francisco International	(*)
	Metropolitan Oakland International	
	San Jose Municipal	
Chicago	O'Hare International	(*)
	Midway	
New York	J.F. Kennedy International	(*)
	La Guardia	(*)
	Newark International	(*)

* - Primary Airport

The seven terminal areas were subjected to route structure development by the application of the Task Force terminal area model. Time phased designs for the 1972-77, 1977-82 and post-1982 time period were developed for two runway configurations at the seven terminal areas. The route structures at the primary airports were then subjected to an analysis of route length and altitude restriction effects upon four types of turbojet aircraft. These analyses were performed for the major airport in six of the terminal areas and for all three New York area airports. Economic comparisons were made between the post-1982 route structures and the current 1972 radar vector/VOR route structure. Two 100% VNAV designs were developed, and were analyzed with respect to separation requirements, airspace utilization, user economic impact, and procedural considerations.

Two New York terminal designs from this initial design effort (1972-1977 and 1977-1982 transition time periods) furnished the basis for a comprehensive real time simulation effort at NAFEC [Reference 13]. The simulation was designed to determine the controller's ability to operate in a mixed VOR-RNAV environment during the transition period. Data on the impact of RNAV on the user, controller workload and system capacity were also recorded.

The results of all these terminal design analyses tended to point out some apparent weaknesses in some elements of the Task Force terminal design model. In order to correct these weaknesses a modified Task Force terminal design procedure was developed. This procedure called for a greater use of the traffic density and direction of traffic flow information for the terminal area. In addition, vertical route profiles which could accommodate varying aircraft climb performance and descent procedures were used. This modified design procedure was applied to the New York terminal area. The resulting

New York terminal area design was then subjected to a route length and altitude restriction analysis program. The results of this analysis indicated that a considerable improvement in user benefits (time and fuel) could be expected if such a design were applied to New York area operations.

The modified New York route structure was used in a second real time simulation effort at NAFEC [Reference 18]. This simulation differed from the transition period simulation in a number of respects. First, increased traffic demands were imposed upon the controllers in order to determine what effects upon terminal capacity would be observed as area navigation equipped aircraft operations were increased. Second, 3D RNAV (VNAV) equipped aircraft were used in the simulation at several participation levels in order to identify unique ATC problems in handling these aircraft. Third, some additional degree of realism was given to the aircraft targets by incorporating a navigation error model into the simulation facility. The error model produced flight paths that differed from the nominal by an amount that was representative of errors that can be found in actual aircraft operations. In addition to these error models for simulated targets two general aviation trainers (GAT), containing representative GA RNAV and VNAV systems, were connected to the simulation facility. These GAT aircraft were operated by NAFEC pilots and were controlled in the simulated Kennedy airspace in the same manner as the aircraft targets generated by the digital simulation facility (DSF). One final difference in this simulation should be noted. Five field controllers were used as DSF controllers along with the regular NAFEC facility controllers. The field controller comments regarding this RNAV/VNAV simulation project can be found in Appendix E of this report.

In order to confirm the validity of the modified RNAV route design procedure from an ATC viewpoint, a series of briefings were held at the FAA regional offices for six of the seven terminal areas. At these briefings, terminal and enroute controllers and FAA regional personnel stated that the original Task Force terminal design concept appeared to be overly restrictive and should not be used at every terminal area due to its inherent lack of consideration of local problems. In general the field controllers endorsed the modified design concept. Also, at these briefings, detailed discussions of the time phased route structures were held. The controllers indicated that the 1972 designs, with some minor changes, accurately depicted the terminal area route structures and procedures that were in use in that time period. However, most controllers felt that the 1977 and 1982 designs, which were based on a fairly strict application of Task Force concepts, would be difficult, if not impossible, to implement in their particular area.

From the discussions with the controllers it was evident that further design guideline development and a second design effort was necessary in order to produce potentially viable RNAV terminal route structures. Consequently, a redesign effort was initiated for all seven of the terminal areas and a set of recommended terminal area design guidelines was developed. A technique was developed which aided in identifying terminal waypoint locations which would be of benefit to the user. This technique was used as the primary means of selecting the arrival and departure sectors in the

final designs. In addition, a vertical envelope concept of waypoint altitude selection was utilized.

A vertical envelope concept was applied to arrival routes which would accommodate both 2D descent procedures and pilot selected 3D gradients for arrival aircraft. It was determined that dedicated, fixed gradient, VNAV arrival routes provide no benefit over a well designed structure which takes into account optimum descent profiles from either an airspace utilization or user benefit viewpoint. The user of pilot-selected VNAV descent procedures within the vertical arrival envelope can produce significant user time or fuel benefits during the deceleration and descent phase of flight.

Vertical departure envelopes were also provided to accommodate a realistic range of aircraft climb capabilities in the departure routes, rather than specifying fixed gradient departure routes which would impose a penalty on the user. Selected high performance departure routes were also developed for the final New York design. These high performance routes were developed in places where shorter route lengths to the boundary of the terminal area could be achieved if a minimum gradient can be attained by the aircraft using the route. High performance departure routes with shorter route lengths from the conventional envelope departure routes were not possible in the other six terminal area designs. Analysis of this type of vertical envelope design concept indicated that high performance departure envelopes provide a definite benefit to the user. Both time and fuel savings were achieved by aircraft using the high performance envelope rather than the corresponding route which was available to all aircraft.

The resulting designs were subjected to route length and altitude restriction analyses in order to determine if there were identifiable user benefits for these routes. In all seven terminal areas, significant improvements over VOR/vector routings in both terminal transit time and fuel consumption were obtained for the RNAV terminal routes based on the recommended terminal area design guidelines which are contained in Section 8.

1.2 APPLICATION OF THE TASK FORCE MODEL

The Task Force RNAV terminal model was applied to seven terminal areas (13 airports) in the initial design effort. Time phased designs were created at all seven terminal areas. The first time period designs, 1972-1977, were based heavily upon current terminal areas procedures. RNAV routes in this time period often were essentially coincident with current radar vector and VOR routes. The second time period designs, 1977-1982, were based upon accommodating both RNAV and VOR aircraft. The Task Force design was used to the maximum extent possible under the constraint of maintaining a satisfactory VOR traffic flow utilizing current navigation facilities at their present locations. The third time period design, post-1982, which assumed a 100% RNAV environment, made use of the Task Force terminal area model to the maximum extent possible based upon the constraints of the characteristics of the terminal areas. The sequence of design development began with the design of the 1972-1977 RNAV routes based on the present VOR route structure. Then the post-1982 RNAV routes were developed and the design effort for each terminal area concluded with the development of the mixed RNAV-VOR route

structure for the 1977-1982 time period, since the 1977-1982 design was to provide for the transition to the all RNAV structure of the post-1982 period. The major perturbing factor in the application of the Task Force design in Post-1982 designs was caused by multiple major airports in the terminal area and by complex runway layouts which necessitated modification of the terminal routes that were near the airports.

1.3 ANALYSIS OF RNAV TERMINAL DESIGNS

The 2D RNAV terminal designs were analyzed by measuring time and fuel consumption values for four turbojet aircraft. Time and distance values were computed using standard aircraft performance data from handbook values. The time and fuel consumption parameters were computed for all 1982 terminal area designs for the primary airport at each terminal area plus all three airports at New York. The time and fuel consumption values for the 1972 designs were computed as well. The 1972 routes, which represent the current radar vector/VOR route structure, were used as a baseline for comparision of results. Several of the RNAV designs, based on a rigid application of the Task Force principles, yielded significant time and fuel savings while others showed either no savings or a penalty.

An investigation of the reasons behind this mixed benefit situation was performed. The major items which imposed penalties on the designs were the altitude restrictions on heavily traveled routes. These altitude restrictions were often imposed at route crossings that occurred at locations which were based upon strict adherence to the octant concept. Consequently, a modified technique was developed which overcame these characteristic difficulties in the Task Force design model. This modified design technique was developed specifically to improve the time and fuel benefit parameters for RNAV equipped aircraft operating in the terminal area. The modified Task Force design technique was applied to the seven selected terminal areas and increased time and fuel benefits were obtained for all nine major airports in the seven terminal areas.

The real time simulation of the 1972-1977 and 1977-1982 transition period designs [13] indicated that the controllers could operate efficiently in a mixed VOR/RNAV environment. The results of the simulation for both time period designs consistently showed a substantial reduction in the controller workload as the percentage of RNAV aircraft increased. This workload reduction is noted by a reduction in the number of radio contacts and in radio communications time. The type of messages used by the controller changed as the percentage of RNAV traffic increased. The controller had to use significantly fewer radar vectors to control the flight path of RNAV equipped aircraft as opposed to the radar vectored aircraft. The number of speed commands did not change significantly as the percentage of RNAV aircraft increased.

The results of the post-1982 real time simulation project [18] confirmed the results obtained in the initial simulation project concerning controller workload and produced new findings concerning terminal area capacity and the use of VNAV procedures in terminal area operations. With one exception all ATC and user benefit parameters showed either no effect or improvement as the RNAV/VNAV level increased. In particular, sizable reductions in controller workload parameters like the number of radio contacts (-36%), radio communication

time (-42%) and broken RNAV/VNAV clearances (-48%) were observed as the percentage of area navigation equipped aircraft increased. From a user benefit standpoint arrival start point delays (center holding) were significantly reduced (-34%) as the use of RNAV/VNAV equipment increased. Small improvements in arrival distance flown (-3%), arrival time in system (-6%) and arrival rate (+3%) were noted with increased area navigation participation levels. Departure statistics were generally unaffected by the increased use of RNAV/VNAV equipped aircraft. The one exception to the increased benefits trend was noted by increased values for departure time in system (+8%) for VNAV departures. This increase was probably caused by slower airspeeds due to higher rates of climb for the VNAV equipped aircraft departing the terminal area on steep VNAV gradients. The use of these steep departure gradients may actually result in user benefits because the aircraft spends a higher percentage of time at the more economical cruise altitude. Consequently, the user impact relative to the departure time in system parameter are inconclusive.

An analysis of the all-VNAV terminal area design concept, with fixed gradient 3D route segments, was also performed. It was determined that a 100% fixed gradient VNAV concept results in a much more rigidly structured design which affords little flexibility for impromptu routings and which imposes economic penalties on the users. New procedures and possibly new ATC display techniques would have to be developed to monitor aircraft position within the VNAV tubes. Navigation accuracy considerations combined with the large vertical separation between fixed gradient 3D routes required by route geometry result in little improvement in airspace utilization over a well designed envelope structure. The analysis supported the use of the departure envelope concept in lieu of fixed gradient VNAV departures. The envelopes do not require special procedures, they do provide good airspace utilization, and they also provide a significant economic advantage to the user compared to constant gradient climbs. Similarly, the use of a vertical envelope concept for arrival traffic provides a user benefit for both RNAV and VNAV equipped aircraft. A greater benefit can be achieved by the VNAV equipped aircraft operating in the vertical envelope design because the VNAV equipped aircraft can adhere more closely to an optimum descent profile through pilot selection of the desired gradient.

1.4 RECOMMENDED DESIGN PROCEDURE

A modification to the Task Force design procedure was developed which is designed to optimize airspace utilization and user benefits.

The basic features of the recommended design model are as follows:

(1) The terminal area is divided into a terminal maneuvering area (within 15 nm of the center) and a terminal transition area (15-45 nm from the center). The terminal maneuvering area is oriented according to runway considerations as suggested by the Task Force. The terminal transition area is oriented to accommodate traffic flow rather than runway orientation.

(2) The strict application of the octant concept is modified to provide alternating arrival and departure sectors whose size and number are dependent upon traffic flow and demand.

(3) A band of climb and descent profiles which closely approximate optimum handbook profiles are used. Route independence is provided by moving routes and imposing or modifying altitude restrictions if necessary.

(4) Low altitude traffic is not constrained to the flow pattern of the arrival and departure sectors in the terminal transition area,in order to avoid undue route length penalties.

(5) An arrival envelope concept is used which permits aircraft to select any descent procedure which can be accomplished within the bounds of the altitude restrictions defining the envelope. In areas where airspace is limited, a standard 300 ft/mile descent gradient is used along with level deceleration route segments. VNAV equipped aircraft may use their equipment to determine their optimum start descent point in the arrival envelope, while aircraft with only 2D RNAV capability may begin their descent earlier in order to insure reaching the next lower altitude prior to the required position.

(6) A departure envelope concept is also used which accommodates a realistic range of aircraft climb capabilities for all conventional departure routes.

(7) High performance departure envelopes are developed in those areas where a minimum altitude gradient would provide a shorter route for higher performance aircraft. The high performance envelopes are bounded by a "floor" and a "ceiling" which are defined by altitude restrictions at specified waypoints.

The recommended design guidelines were applied to the seven terminal areas. Design aids were developed which produced terminal waypoint locations to define routes which were of benefit to the user. Also, desired vertical profile overlays were developed to aid in the selection of desired crossing altitudes at each of the terminal waypoints for the design of both arrival and departure routes. The recommended guidelines were successfully applied to six of the seven terminal areas. However, some additional design constraints were necessary in the complex New York area. Consequently,additional design guidelines were developed for metroplex areas. These additional guidelines include:

(1) The size and orientation of the terminal maneuvering areas around each airport are determined by the necessity to have independent, conflict-free routes in the vicinity of each airport. Specific lateral and vertical airspace limits for each maneuvering area are dependent upon the relative location of each airport within the metroplex.

(2) Each major airport should generally have its own independent arrival waypoints and routes in the high density arrival areas. Satellite airports may use the same arrival routes as the major airports if the traffic flow is compatible. Separate routes for satellite fields may be used if there is an operational benefit to either ATC or the user if sufficient airspace is available. Arrival routes to major

airports may be merged in low density arrival areas if there is an operational benefit for either ATC or the user.

(3) Departure routes from the major airports may be merged if compatible flows and altitudes can be obtained and if the combined traffic density does not saturate the route and produce departure delays.

With these additional metroplex guidelines, an RNAV route structure was developed for the New York terminal area. All seven final terminal area designs were found to provide substantial user benefits for 2D equipped aircraft, with additional benefits available through pilot selection of 3D gradients.

1.5 MAJOR CONCLUSIONS

Several major conclusions were drawn from the terminal area design study. First, the use of the recommended design concept is preferable to strict adherence to the Task Force model in order to provide optimum airspace utilization coupled with maximum time and fuel benefit to the user. In particular benefits to both the user and ATC resulted from the flexibility that is inherent in the recommended design procedures. Terminal area traffic arrival and departure sectors are aligned with enroute traffic flow to produce a more systematic and consistent terminal and enroute transition than was produced by the Task Force concept. The number and size of the terminal arrival and departure sectors are determined by traffic demand and enroute traffic alignment rather than based upon an arbitrary eight sector, equal size constraint that was endorsed by the Task Force. The use of the recommended guidelines in metroplex areas like New York permitted route structures with fewer altitude restrictions and more compatible arrival and departure routes to the various airports than did route structures that were based upon strict adherence to the octant design. In addition low altitude and short range flights (less than 200 nm) in all terminal areas should not be constrained to specific arrival and departure sectors beyond the immediate vicinity of the airport (10-20 miles). The removal of this constraint can save these aircraft several flight miles by permitting them to fly to and arrive at their destination along shorter, straighter routes than by forcing them to adhere to an arbitrary arrival or departure sector.

A second major conclusion to be drawn is that route structures based on the vertical envelope concept provide significant user and controller benefits for both arrivals and departures while incurring little if any penalty in airspace utilization as compared to fixed gradient VNAV routes. The substantial user benefits for routes designed with the vertical envelope concept accrue to 2D RNAV equipped aircraft, with additional benefits accruing to VNAV equipped aircraft. Fixed gradient VNAV designs produce user penalties and also produce air traffic control problems due to the inherently complex route structure.

Another conclusion that came as a result of this study indicates that early benefits to the users can be achieved through the use of the recommended terminal design guidelines as set forth in this report. The use of these guidelines often result in compatible traffic flows for the existing VOR/radar vector traffic and the RNAV route structure. As the demand for RNAV routes

grows, the terminal area RNAV routes can be implemented on a demand basis. Because of the compatibility between the two structures, the RNAV routes may be implemented with a minimum of changes to current ATC procedures while at the same time providing benefits to the users of RNAV equipment. This step-by-step RNAV route design technique in the terminal area provides a means of progressing from a primarily VOR/radar vector structured airspace to a predominantly RNAV structured airspace without radical changes in existing traffic flows.

The results of the real time simulation of the three New York route structures indicate that controller workload decreased as the percentage of RNAV and VNAV equipped aircraft operating in the terminal area increased. These workload reductions continued to be observed when the operation rates were at full capacity levels. In the post-1982 simulation the terminal arrival capacity, measured in terms of arrivals per hour, increased as the percentage of area navigation aircraft increased. Based on statistical regression analyses of the simulation results, an average arrival capacity increase of 3% was observed for the 100% RNAV/VNAV equipped case versus the 100% radar vector case. No significant change in departure capacity was noted as the percentage of equipped aircraft increased.

The results of the real time simulations of New York Kennedy for all three time periods indicate that the use of RNAV procedures are more responsible for controller workload reduction than are the specific characteristics of the RNAV route structure. This observation is probably true in terms of arrival capacity increases, also. Thus controller workload reductions and arrival capacity increases can be expected in terminal area operations as RNAV aircraft and the use of RNAV control procedures are increased with or without changes in the terminal area route structure.

As evidenced by the real time simulations of the New York Kennedy airspace, the Task Force design guidelines and the recommended design guidelines produced route structures which were capable of being implemented in the simulation at NAFEC. Some minor adjustments of route locations in the terminal maneuvering area for all three time period designs produced routes which permitted more controller flexibility than did the original designs. Consequently, the basic design philosophy should be capable of producing route structures which can be implemented in actual terminal areas.

The final conclusion that was developed during the course of the study was that the design of enroute, transition area and terminal area route structures should be a coordinated effort. It was determined in this study that alignment of the terminal arrival and departure sectors should be made on the basis of traffic flow in order to increase user benefits. In order to continue to accumulate these benefits the transition and enroute traffic flows must be connected together in a manner which involves straight flight paths with a minimum number of attitude restrictions. This can only be assured if the route structures for all three airspace regions (terminal, transition and enroute areas) be developed on a coordinated, systematic basis for the entire United States.

2.0 BACKGROUND AND METHOD OF APPROACH

This document is the final report of a study program of terminal area design applications based upon the use of area navigation (RNAV) and vertical navigation (VNAV) equipment and procedures.

The objectives of the study were as follows:

(1) To evaluate and validate the basic terminal area RNAV and VNAV design guidelines which were included in the FAA/Industry RNAV Task Force Report [1] through their application to several specific terminal area environments.

(2) To provide terminal area designs, for the three RNAV implementation time periods, to be used in the operational analysis of a mixed VOR/RNAV environment and in the evaluation of terminal area ATC procedures and phraseology through real time simulation experiments [References 13 and 18].

(3) To provide a series of terminal area RNAV designs, representative of characteristic high and medium density hubs, which would serve as a basis for part of the analysis of the economic impact of area navigation implementation on the airspace user and the ATC system operator through analytical studies and simulation programs [References 3 and 16].

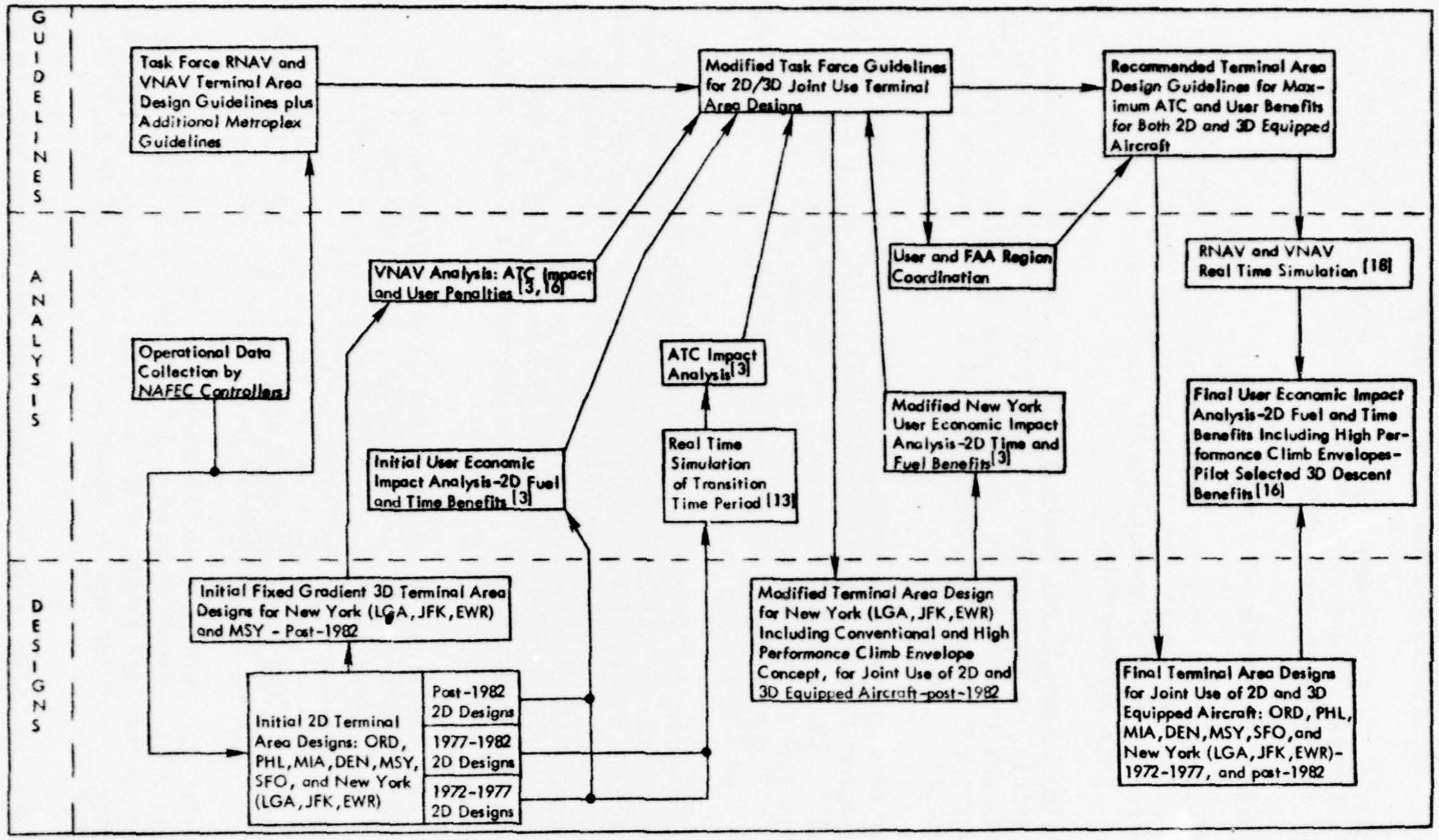
(4) To provide terminal area RNAV route structures which could be used in flight evaluations involving both general aviation and airline type RNAV equipment, for the purpose of developing procedures and phraseology, verifying Task Force [1] recommended equipment error budgets, analyzing pilot workload and flight technical error, providing data for the development of RNAV Avionics Standards and for input to the economic impact analysis [References 17, 20 and 21].

(5) To identify route design characteristics and criteria for the terminal area as an input to an analysis and development of way-point designation standards, including the potential use of grid systems [Reference 19].

(6) To investigate the interaction between the Task Force [1] recommended terminal area and enroute design guidelines [Reference 2].

(7) To develop the information necessary to produce a set of RNAV Terminal Area Design Guidelines which incorporates the principles defined by the Task Force, which are tempered as appropriate by consideration of the results of studies identified in objectives 1-5 above.

The chronology of the terminal area study and related analyses is detailed in Figure 2.1.



[ ] Indicates Report References In Which Results Appear

Figure 2.1 Development of Terminal Area Design Guidelines

At the initiation of this study program, NAFEC controllers collected operational data on fourteen high and medium density terminal areas throughout the U.S. in order to identify current operational procedures. These terminal area data packages were utilized to develop initial time-phased designs for seven terminal areas (13 airports). The Task Force Terminal Area Model was applied to the post-1982 designs (100% RNAV traffic) for all seven terminal areas. For those terminals whose traffic was dominated by a single major airport, the Task Force terminal model could be applied directly with limited modifications required. This was the case of the Denver, Philadelphia, Chicago, New Orleans and Miami terminal areas. The metroplex areas of New York and San Francisco required considerably more modification to the Task Force model, due to conflicting traffic flows to and from the major airports.

Initial terminal area designs for the 1972-77 transition period were developed for the seven terminal areas. In general, RNAV routes were designed to overlay current radar vector routes in the terminal maneuvering area (within 15-25 nm of the center of the airport) and to coincide with VOR routes outside the terminal maneuvering area. The initial 1977-82 transition designs were based on the initial post-1982 designs, modified as required to accommodate a VOR route structure.

The initial designs were analyzed from both an ATC system and airspace user point of view, and, based on these analyses, a set of modified Task Force guidelines was developed for terminal area designs for joint use of both 2D and 3D equipped aircraft. The analyses were based on the results of a real time simulation of the New York design [13], user and system economic impact analyses [3], and a study of VNAV separation and procedural considerations detailed in Appendix A of this report. The modified guidelines were first applied to the New York terminal area for the post-1982 period and the resulting design was subjected to a user economic impact analysis to insure that the modified design guidelines would produce maximum fuel and time benefits for the user. This post-1982 New York terminal design was used as the basic route structure for a second real time simulation effort in which terminal area capacity, controller workload and user benefits were analyzed for RNAV, VNAV and radar vectored aircraft [18].

The results of the initial design effort, including the modified design guidelines and the modified New York design, were reviewed with user groups and with controller and supervisory personnel at the appropriate FAA regions. Based upon comments received in these review meetings, and on the results of the ATC and user impact analyses, a set of Recommended Terminal Area Design Guidelines was developed. Based on these recommended guidelines, "final" terminal area designs for all seven terminal areas were then developed for the 1972-1977 and post-1982 periods. These final post-1982 designs were subsequently analyzed for user economic impact and found to be superior to the initial designs.

The data sources used in the study and the techniques used in the application of the Task Force design model to the initial terminal area designs are given in Section 3. The analysis techniques applied to the designs and the technical approach utilized in the development of the modified design guidelines

are given in Section 4. Section 4 also includes a discussion of the review of the modified design guidelines with user and ATC personnel and the development of the recommended terminal area design guidelines, which are included in Section 8. Both the initial and final terminal area designs for the 1972-1977 period are described in Section 5. Section 6 presents the initial terminal area designs for the 1977-1982 period. (Final designs were not developed for this transition period). Both the initial and final designs for all seven terminal areas for the post-1982 period are described in Section 7. Section 7 also includes an interim, or "modified" post-1982 New York design which was developed for the purpose of verifying the expected improvement in user benefits through the application of the modified design guidelines. The recommended terminal area design guidelines, which evolved from the modified design guidelines through regional controller participation, are presented in Section 8. Examples of airspace design techniques are discussed along with a step by step procedure for developing RNAV oriented terminal route structures. The study conclusions are presented in Section 9. Conclusions concerning the general design principles are discussed along with conclusions relating to terminal routes in the three time phased RNAV implementation periods. Finally, several conclusions involving VNAV terminal route design applications are presented.

3.0 DATA SOURCES AND TASK FORCE DESIGN MODEL

The RNAV Task Force recommended a time phased implementation of RNAV, and provided for two transition periods, 1972-1977 and 1977-82, in which terminal area designs would be based on compromises between the post-1982 RNAV concept and the requirements for retaining VOR routes and to accommodate non-RNAV operations. The technical approach to the terminal area design study has been structured to produce designs based on the Task Force concepts, to use those designs in an analysis of the ability of the pilot and the controller to operate in a mixed VOR/RNAV environment, to analyze the designs from both the ATC system and airspace user point of view, and to develop a set of recommended terminal area design guidelines for the three time periods.

This section identifies the data sources used in the study and describes the technique developed for the application of the Task Force terminal area design concepts to the initial set of terminal designs.

3.1 TERMINAL AREA DATA SOURCES

The major source of data and information on present terminal area design was furnished by the National Aviation Facilities Experimental Center's (NAFEC) Simulation and Analysis Division. In answering a request for information on the seven high density terminal areas and seven medium density terminals listed in Table 3.1, NAFEC dispatched a team of controllers to visit the fourteen terminal areas and collect all available information on the present operational procedures in these terminal areas. Information was subsequently obtained for the Miami terminal area also. Miami was added to the design effort because RNAV routes and procedures were developed and used at this ATC facility. A list of representative sources of information that were obtained in this data collection effort is shown in Table 3.2. This information was used to develop the current traffic flow patterns used in the terminal area for both primary and satellite IFR airports.

TABLE 3.1 TERMINAL AREAS VISITED BY NAFEC CONTROLLERS

High Density Terminals	Medium Density Terminals
New York	Cincinnati
Atlanta	Minneapolis
Chicago	Albuquerque
San Francisco	Indianapolis
Los Angeles	Kansas City
Philadelphia	New Orleans
Washington, D.C.	Denver

Three other sources of terminal data were used in the initial design analysis. First, preferred route listings in the Airman's Information Manual (AIM)[10] were used to determine current terminal-enroute connecting routes for those cities listed. The second additional source of data was the Peak Day Enroute IFR Traffic Report for 1971[9] and the third data source was the 1969 peak day tape of enroute IFR operations. In this report are listed city pairs which exchanged ten or more IFR flights on the peak day records. From these

TABLE 3.2 TERMINAL AREA DATA RESOURCES

Standard Operating Procedures Manual (SOP Manual).
Letters of Agreement between the Terminal Facility and Adjacent Terminals, Centers and Towers.
Terminal Airports, Runways and Facilities.
Current Radar Vector Routes and VOR Routes.
Current Arrival and Departure Fixes.
Runway and Fix Utilization Data.
Radar and Non-radar Procedures.
Current SID, STAR and Instrument Approach Procedures.
Control Jurisdictions and Sectorization.
Noise Abatement and Other Special Procedures.

lists traffic distribution diagrams were constructed for the terminal areas which were being analyzed. The airspace around the terminal was divided into 15° segments. The traffic within each segment was obtained by connecting the terminal city with each city listed in Reference 9 as exchanging ten or more flights per day with the terminal city and summing all the operations that fell within that segment. It was found desirable to divide the traffic distribution diagrams into high and low altitude operations. Since the traffic was not listed in this manner, some assumptions were made based upon mileage between the city pairs in order to obtain separate high and low altitude counts. The procedure that was used for constructing the traffic distribution diagrams is discussed in Seciton 3.4.4.1.

In addition, the peak day enroute IFR traffic data was used to determine the level of IFR activity at each airport in the terminal area. Arrival and departure data for specified airports on the 1969 peak day tape was divided into four categories.

Low altitude arrivals
Low altitude departures
High altitude arrivals
High altitude departures

From these data a determination was made of the significance of each airport in the terminal area based on IFR operations.

In the development of the terminal area routes based on the modified design guidelines, it was necessary to have more detailed traffic distribution data than that used in the initial design task. Consequently, a new data base for traffic distribution was required. The most readily available source of data of this nature was found to be the Official Airline Guide [15]. Although this data is representative of scheduled air carriers and air taxi operations only, it does present a relatively accurate picture of traffic distribution insofar as jet traffic is concerned. From the standpoint of primary design measurements of time and fuel penalties, the jet traffic is the most critical.

3.2 SELECTION OF TERMINAL AREAS FOR ANALYSIS

From the terminal area data packages collected by NAFEC seven terminals were selected for further analysis. These seven terminals were:

New York	Chicago
Denver	New Orleans
Philadelphia	San Francisco
Miami	

These seven terminals have characteristics which are representative of most problems that would be encountered in terminal area design work. The New York and Chicago terminal areas are very large hubs that accommodate over 2000 IFR operations per day. The San Francisco and Miami areas are large hubs that have more than 1000 but less than 2000 daily operations. Philadelphia and Denver are representative of medium size hubs with daily operations numbering between 700 and 1000. New Orleans is a small hub with approximately 500 operations per day.

New York, Chicago, San Francisco and Miami are metroplex areas which have more than one major airport in the terminal area. New York is certainly the classical example of a metroplex area with three closely spaced major airports in the terminal area. The other three metroplex areas have one major airport and one or more major satellite fields.

The runway layout at Chicago O'Hare is among the most complex in the world with three sets of parallel runways. Miami and Philadelphia have parallel primary runways while Denver, San Francisco, New Orleans and two of the New York airports have runway patterns in which the primary runways are perpendicular to each other. Some of these airports have both perpendicular and parallel runway patterns.

The New York, Philadelphia, San Francisco, New Orleans and Miami areas are coastal cities with unbalanced traffic distribution, that is, considerably more traffic flows in some directions than others. Chicago and Denver have more uniform traffic distributions than do the coastal cities.

High terrain is a factor in the Denver and San Francisco areas while terrain is no problem at the other five areas. The high altitude at Denver is an additional complicating factor in the design due to the reduced climb performance of all aircraft at higher altitudes.

All airports that were analyzed had noise abatement procedures that were considered in all of the subsequent terminal designs. In most cases noise abatement affected either the primary runway selection or the departure route in the terminal maneuvering area.

3.3 THE TASK FORCE TERMINAL AREA MODEL

The basic concepts of the Task Force terminal area model were outlined in Section IV of the RNAV Task Force Report. The guidelines and design principles provided by this report were developed and extended into a design technique that

could be employed at many specific terminal areas. Some design guidelines required further development beyond that contained in the Task Force Report before the Task Force design model could be generally utilized at actual terminal areas. These areas included the following:

- Multiple airport terminals
- Multiple runway configurations
- Low altitude enroute waypoint locations
- Enroute traffic distribution
- Climb profiles at high altitudes

The Task Force terminal area model, with provisions for the preceding operational considerations, was used to develop several terminal area route structures. It was found that the Task Force model could be used to develop route structures that were satisfactory from an air traffic control standpoint but that these route structures were not always optimum from a user benefit standpoint. That is, the route structures that were developed using the Task Force model provided a means for the aircraft to fly from the enroute airspace to the airport or vice versa and be procedurally separated from other traffic in the terminal area. However, some of the route structures that were developed using the Task Force model caused more fuel to be consumed by aircraft and took more time to fly than did current VOR and radar vector routes. In order to develop an RNAV route structure that produced user benefits, a modified Task Force terminal area design model was eventually developed and recommended for use in lieu of the basic Task Force model.

3.4 THE TASK FORCE 2D TERMINAL AREA MODEL

The RNAV terminal area design technique calls for the establishment of an octant* or wagon wheel design for RNAV terminal routes. The major elements of the octant concept are:

- Orientation of the octant design
- Final approach maneuvering area
- Location of waypoints
  - Terminal Area Waypoints
  - Low Altitude Arrival/Departure Waypoints
  - High Altitude Arrival/Departure Waypoints
- Alternate runway use
- Multiple runway use
- Application of the standard terminal area model

The salient points of this design concept are presented in the following paragraphs.

---

* The RNAV Task Force [1] used the term quadrant as they developed their terminal area design techniques. The author prefers the term octant to quadrant because the area around the terminal area is a circle divided into eight equal sectors or octants. Four of the sectors are arrival octants and the remaining four are departure octants.

3.4.1 Orientation of the Terminal Area

The orientation of the Task Force terminal area model is based upon the primary IFR arrival runway within the terminal area. The general hierarchy for IFR arrival runways is as follows:

1) Runway with Category II Approach
2) Longest ILS Equipped Runway
3) Longest Localizer Equipped Runway
4) Longest Runway

Occasionally, however, the longest runway is not a valid indicator of the preferred arrival runway for the terminal area. Consequently, if there exists a preferred runway based upon operational considerations, it may be selected as the primary IFR arrival runway for purposes of octant alignment. Operational considerations include the following factors:

- Enroute Traffic Flow
- Terrain Restrictions
- Multiple Airport Terminal Configuration
- Multiple Runway Configurations

3.4.2 Final Approach Maneuvering Area

The final approach maneuvering area is used by the final controller for final sequencing and spacing functions. A variety of RNAV offset and delay "trombone" tactics are used by the controller in this area for merging and spacing flows from the feeder fixes.

The final approach maneuvering area can be described physically as a 45° sector of a circle with a radius of approximately 20 nm. The angle bisector of the final approach maneuvering area is located on the centerline of the active landing runway and the apex of the sector is located at the center of the active runway.

When the active runway changes, the final approach maneuvering area also changes and is aligned with the new active runway in the same manner as it was aligned with the primary runway as shown in Figures 3.1 and 3.2.

3.4.3 Construction of the Octants

The center of the terminal area is usually determined by using the center of the runway complex. The extent of the terminal area is assumed to be a 45 nm circle located at the center of the runway complex (Figure 3.3). The area within the 45 nm circle is then subdivided into eight equally sized octants. The boundaries of the octants are at angles of ±22-1/2° from the extension of the primary IFR landing runway and are spaced every 45° thereafter (Figure 3.3). The two octants that contain the primary runway extensions are identified as departure octants. Proceeding around the circle, the octants alternate departure, arrival, departure, arrival, etc. The use of a 45 nm circle about the center of the terminal area for design purposes will produce a terminal boundary which will not generally coincide with the TRACON boundary. This fact does not inhibit the use of a standard design concept for producing designs for actual terminal areas. However, if the standard terminal model was used in actual practice it could affect the location of ARTCC-TRACON handoff points.

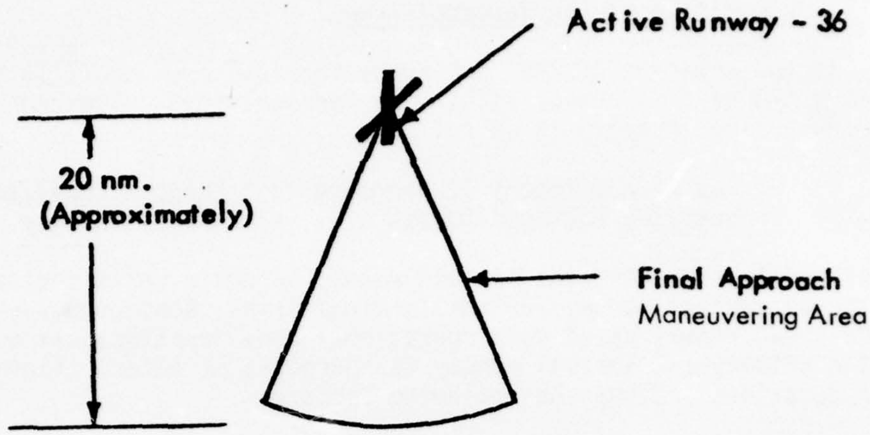


Figure 3.1 Final Approach Maneuvering Area for Runway 36

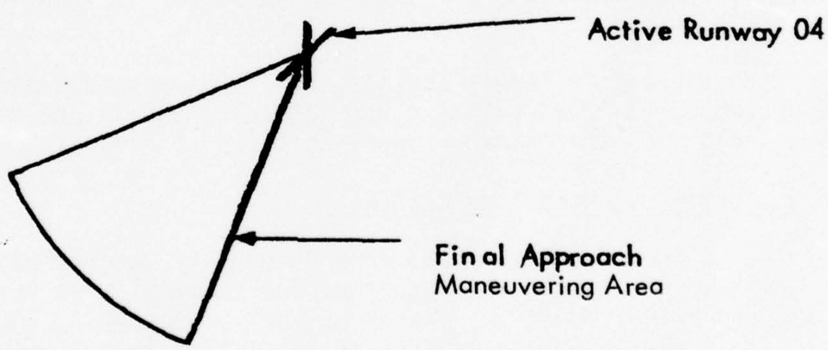


Figure 3.2 Final Approach Maneuvering Area for Runway 04

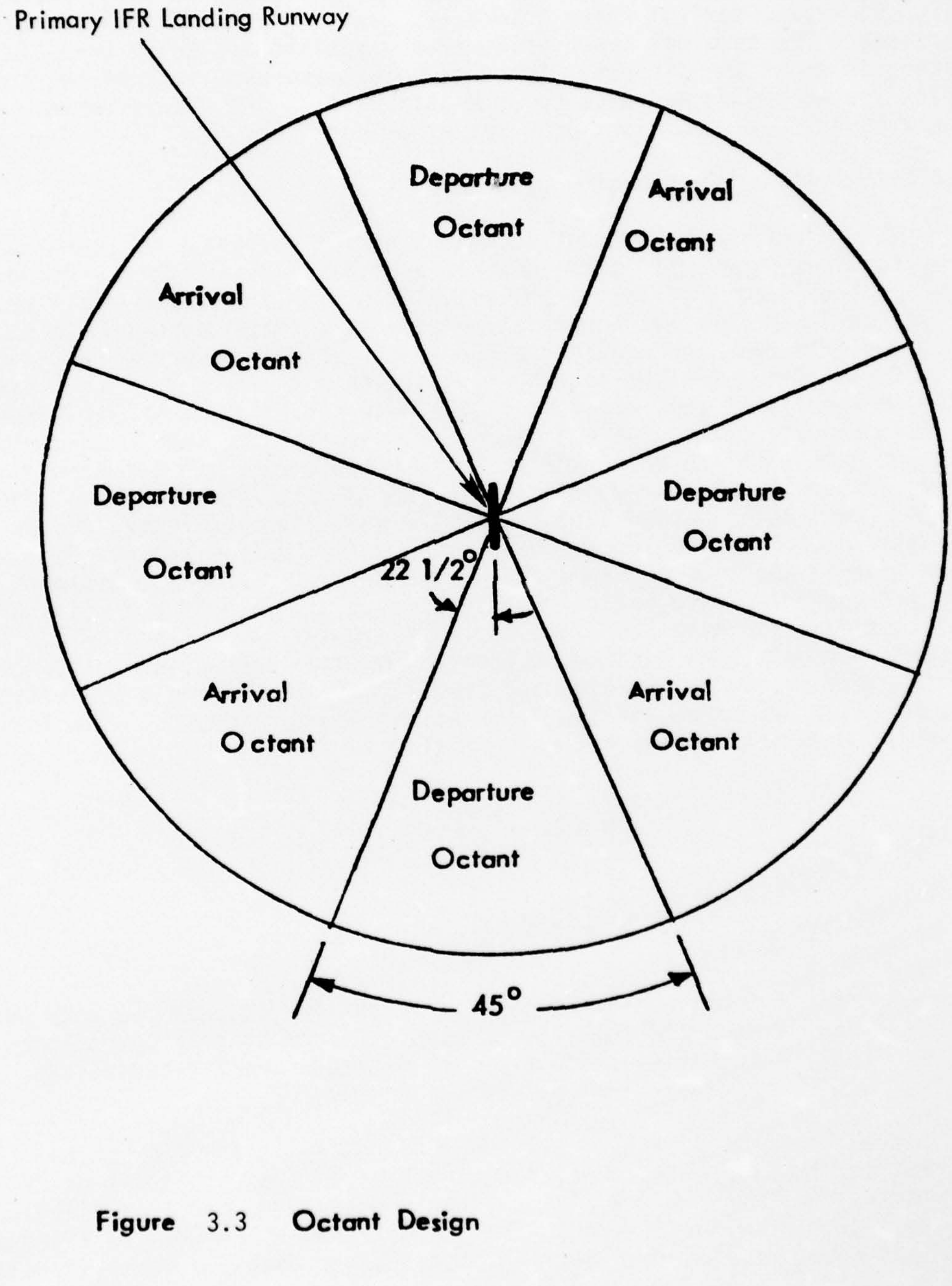


Figure 3.3 Octant Design

3.4.4 Location of Terminal Area Waypoints

The Task Force terminal area design employs the use of a standard waypoint pattern. Terminal area waypoints can be categorized into two types, transition area waypoints and terminal maneuvering area waypoints. The transition area waypoints lie on or near the periphery of the terminal area. Aircraft flying to/from these points are transitioning from/to the terminal airspace. The terminal maneuvering area waypoints are those that lie within 15 nm of the airport. These waypoints are used to position the aircraft for making an approach to or departure from the active runway, and their location is dependent upon runway orientation.

3.4.4.1 Traffic Distribution Diagram

The selection of waypoint locations at the periphery of the terminal area requires knowledge of the desired arrival or departure direction for the terminal area traffic. A convenient tool for determining this traffic direction is the traffic distribution diagram. These diagrams can be constructed from data concerning the number of aircraft from the originating city for arriving traffic and the destination city for departure traffic. Example sources of this data are flight data strips and peak day enroute IFR traffic reports. The airspace around the terminal area was then divided into 15° segments (7.5° on each side of the candidate waypoint locations). By using either computed great circle bearings or a Lambert Conformal Projection of the continental United States (NOS-IFR Wall Planning Chart) the enroute traffic in each 15° sector was determined. The traffic was divided into low altitude and high altitude categories depending upon the distance between the corresponding city pairs. A city to city distance of 200 miles or less was considered to have low altitude traffic only. A distance of 500 miles or greater had only high altitude traffic. For the intermediate distances traffic was divided among high and low altitude traffic on a proportional basis, using 200 miles and 500 miles as the boundary points. The following formulas were used to apportion the traffic:

$$NH = N\left(\frac{D-200}{300}\right)$$

$$NL = N\left(\frac{500-D}{300}\right)$$

where
N = total number of traffic operations between the city pair
NH = computed estimate of high altitude traffic operations
NL = computed estimate of low altitude traffic operations
D = distance (nm) between city pairs

In other words if a city pair were 350 nm apart and they exchanged 60 flights per day, 30 were considered to travel in the high altitude route structure and 30 in the low altitude route structure. If the cities were 300 nm apart then 40 flights were in the low altitude structure, 20 flights were high altitude. Examples of traffic distribution diagrams for Philadelphia are shown in Figures 3.4 and 3.5

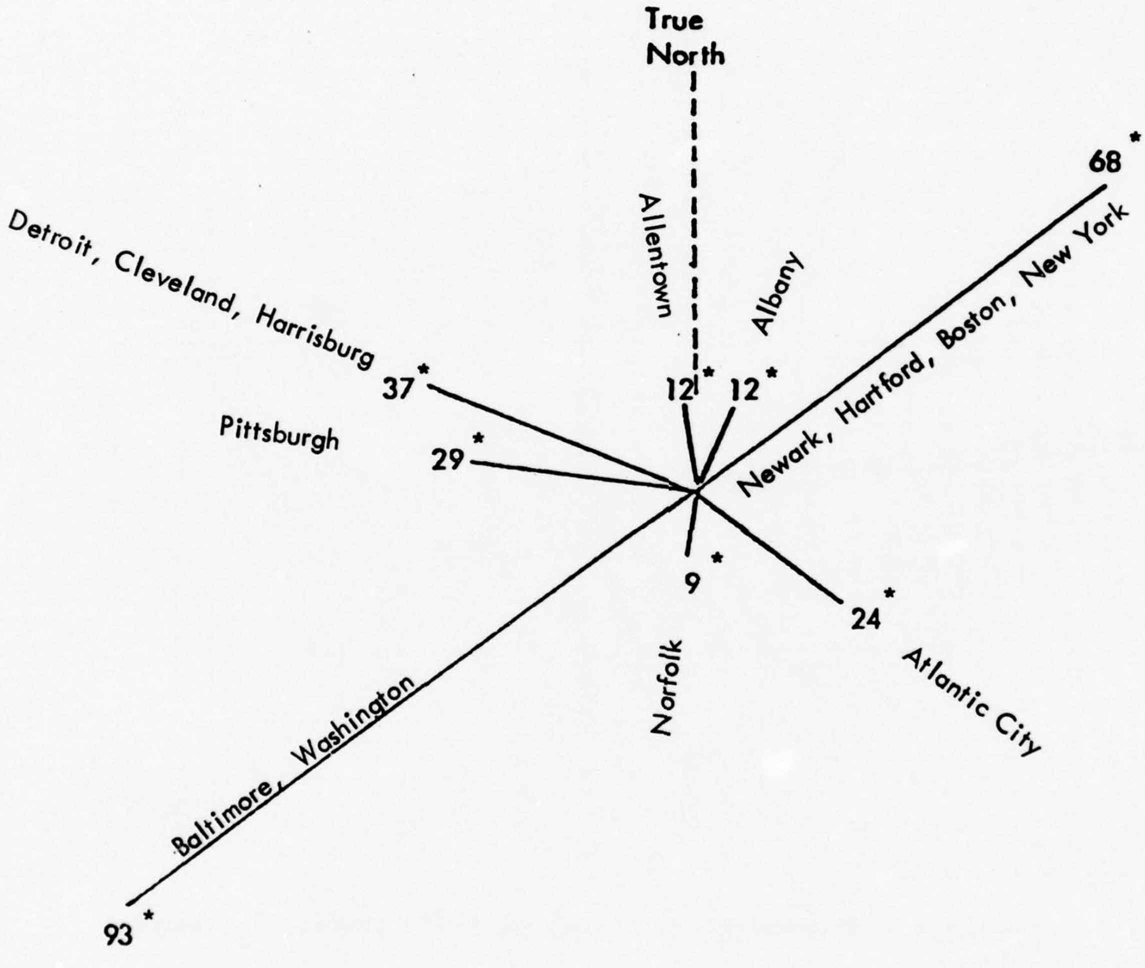


Figure 3.4 Philadelphia Low Altitude Traffic Distribution Diagram

*** Note: Length of the lines corresponds to the noted number of flights exchanged between the subject city in the 15° sectors indicated on the diagram.**

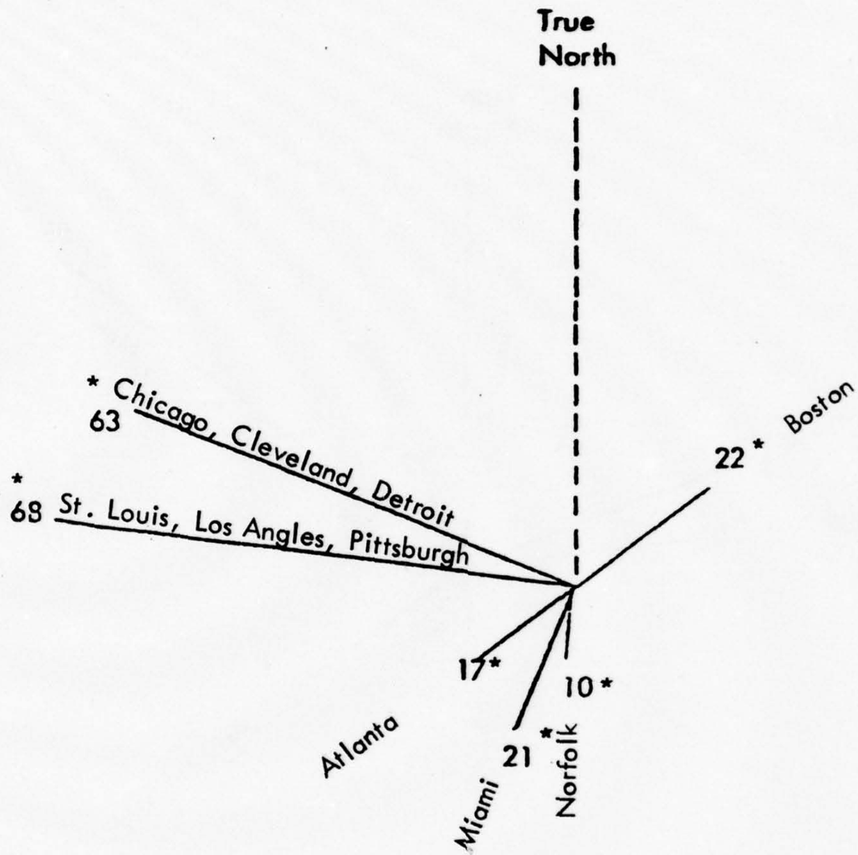


Figure 3.5 **Philadelphia High Altitude Traffic Distribution Diagram**

***Note – Length of the lines corresponds to the noted number of flights exchanged between the subject city in the 15° sectors indicated on the diagram.**

3.4.4.2 Transition Area Waypoints

The specific types of transition area waypoints are:

High altitude departure waypoints (HADWP)
High altitude arrival waypoints (HAAWP)
Low altitude enroute waypoints (LAEWP)
Low altitude departure waypoints (LADWP)
Low altitude arrival waypoints (LAAWP)

These waypoints lie between 14 and 45 nm from the primary airport in the terminal area and remain fixed regardless of the currently active runway.

The high altitude arrival and departure waypoints are located on the 45 nm circle. The candidate locations fall on the bisector of each octant and $\pm$ 15° on each side of the octant bisector for a total of 3 candidate locations for each octant. The determination of which candidate waypoints will be used is based upon the distribution of high altitude enroute traffic around the airport. The high altitude traffic distribution diagram is used for this purpose by applying the following procedure.

The candidate waypoint becomes an actual waypoint if its corresponding 15° high altitude sector contains a significant traffic level (5 flights/day). If that sector is an arrival octant, a corresponding high altitude departure waypoint is selected in the departure octant that is closest to the arrival octant thus providing the shortest distance between the two airports under the constraints of the standard terminal area design. A similar procedure is used when the traffic samples fall in a departure octant. An example of the procedure for determining the location of the high altitude arrival and departure waypoints for Philadelphia is shown in Figure 3.6. Octants that contain no traffic are given one waypoint in the center of the octant.

In most cases low altitude routes are used by short haul traffic. Often this traffic flies between airports that are between 50 and 200 miles apart. To constrain this traffic to an octant flow pattern within the terminal transition area would often cause considerable penalties in distance flown between two closely spaced airports. In order to minimize this problem, the low altitude traffic was permitted to violate the octant traffic flow concept by staying at lower altitudes than the high altitude traffic which was constrained to the octant flow. A candidate low altitude enroute waypoint position was established on the perimeter of the 45 nm circle and on a line between the two airports that were exchanging low altitude traffic. Low altitude departure traffic would pass from the low altitude departure waypoint to the low altitude enroute waypoint while arrivals would pass from the low altitude enroute waypoint to the low altitude arrival waypoint. Consequently, two way traffic was handled over the low altitude enroute waypoint. This traffic was assumed to be at cruise altitude and separated by altitude restrictions. The Philadelphia low altitude traffic distribution diagram is shown in Figure 3.5. The locations of the low altitude enroute waypoints for Philadelphia are shown in Figure 3.7.

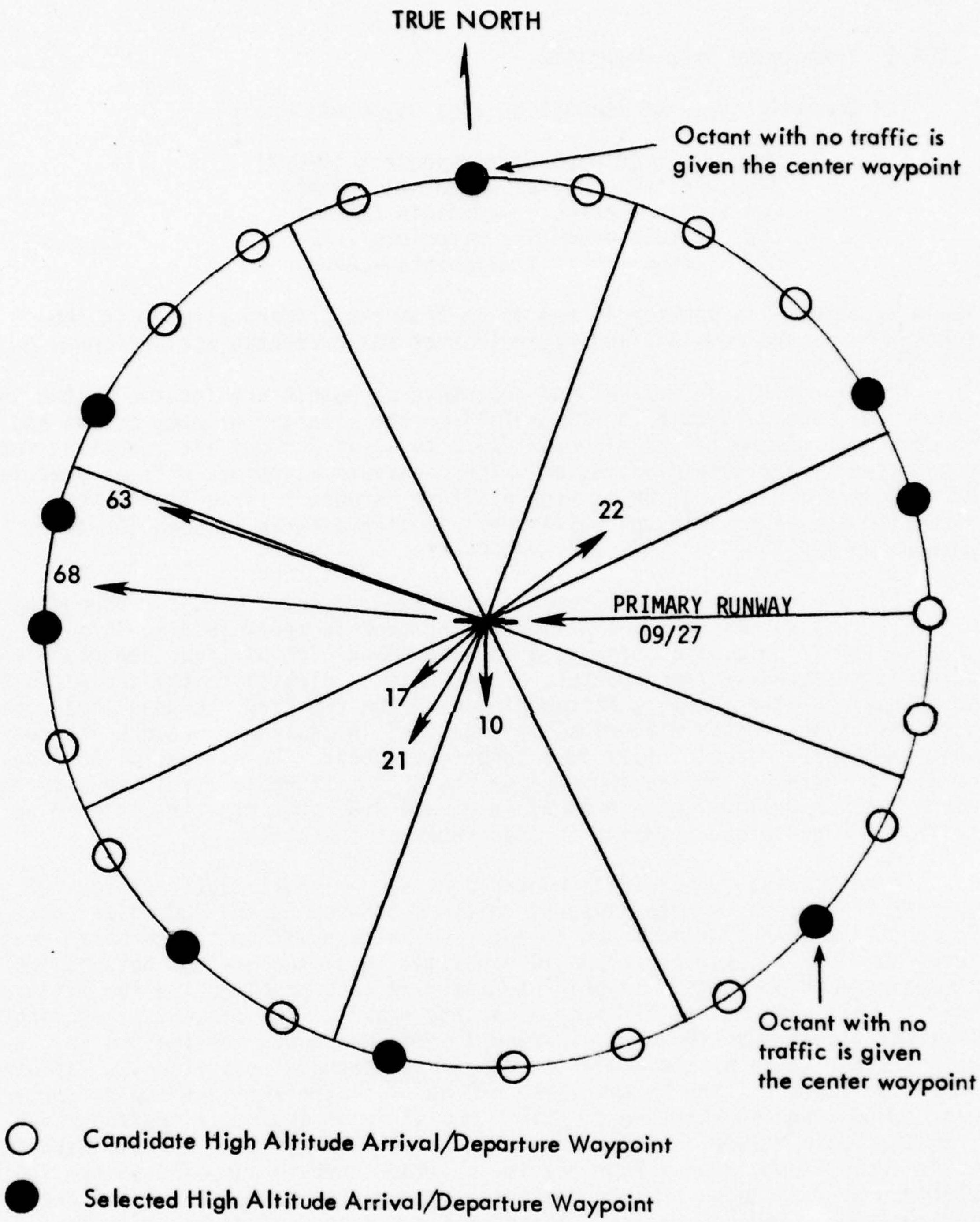


Figure 3.6 Determination of High Altitude Arrival and Departure Waypoints for Philadelphia

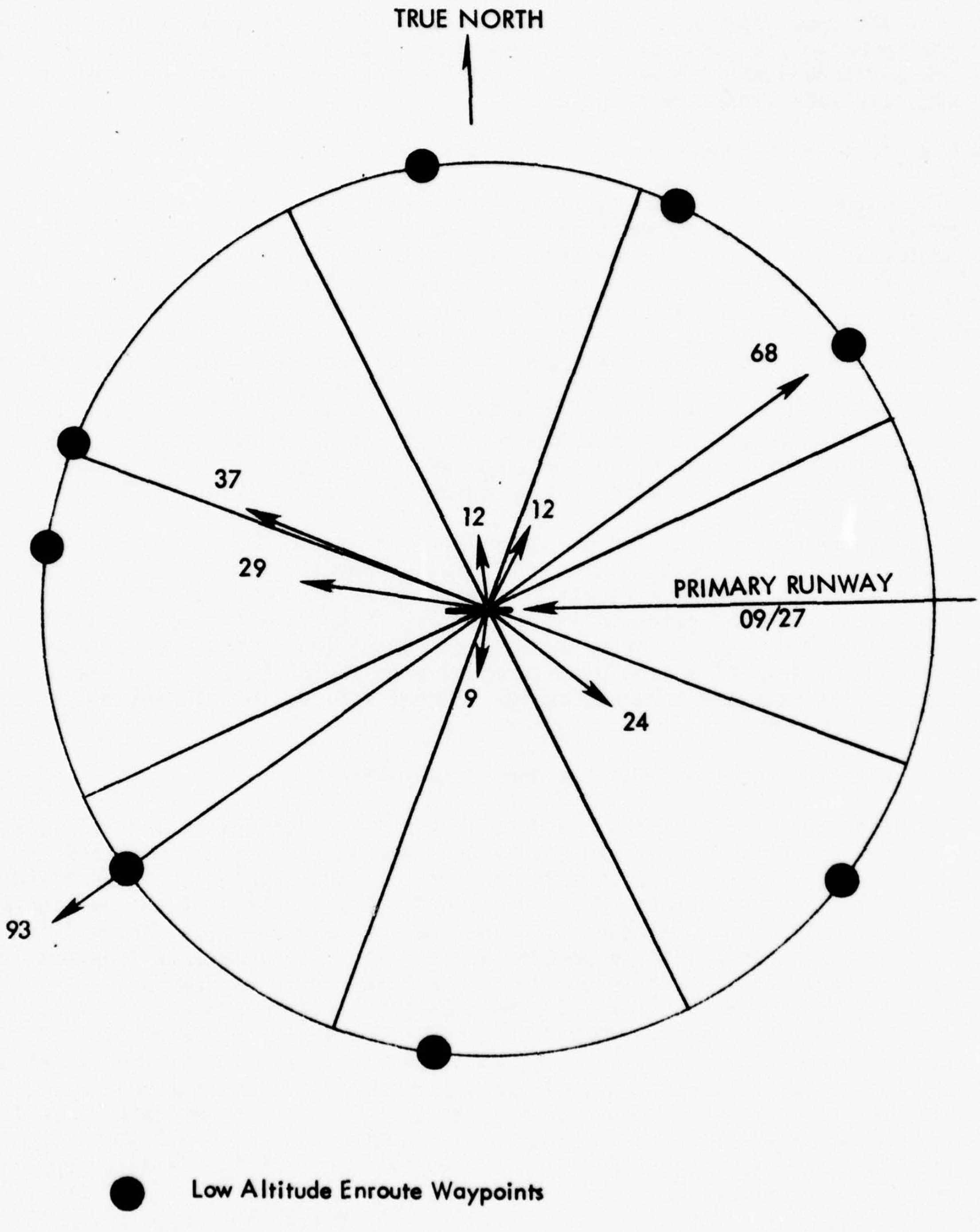


Figure 3.7 Determination of Low Altitude Enroute Waypoints for Philadelphia

Low altitude departure waypoints are located 15 nm from the center of the terminal area on the bisector of the departure octant. Departures proceed from the low altitude departure waypoint to the low altitude enroute waypoint or the high altitude departure waypoint.

3.4.4.3 Terminal Maneuvering Area Waypoints

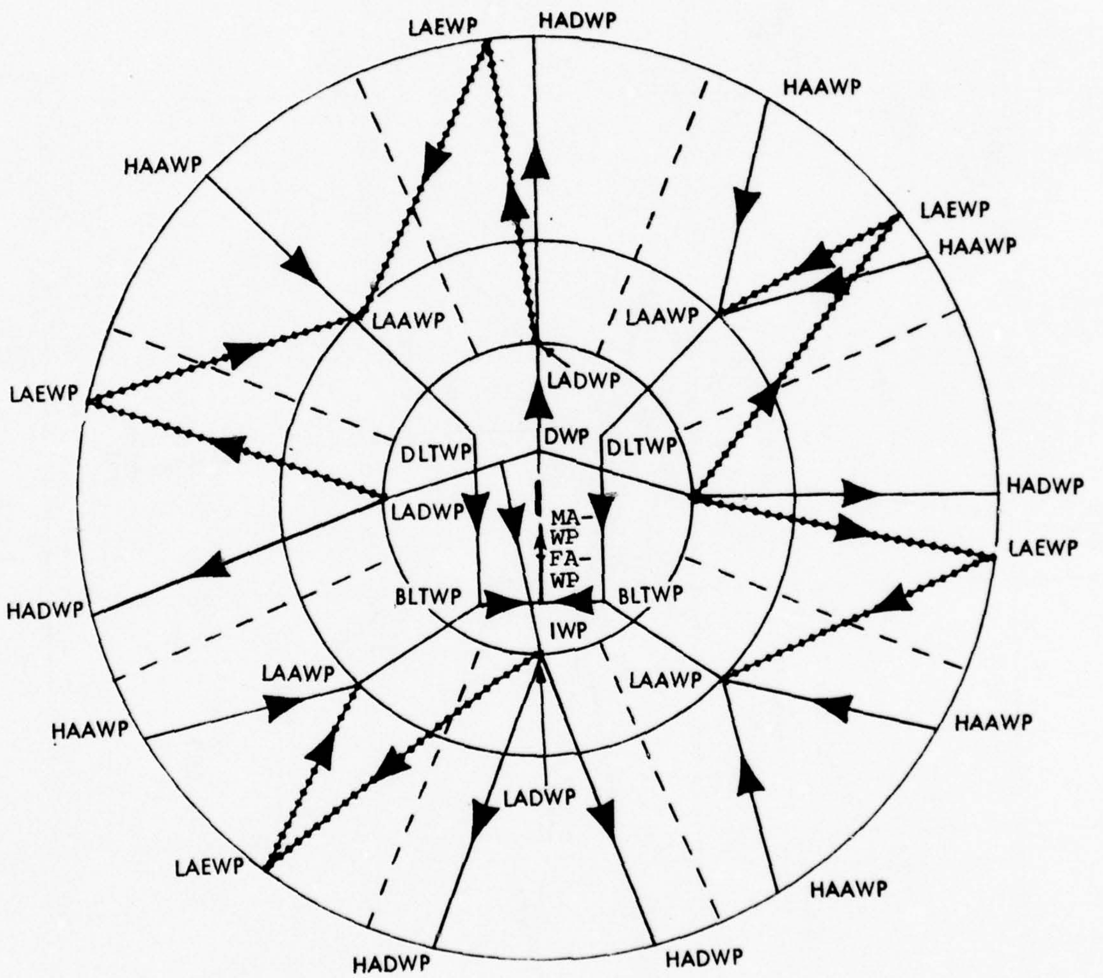
The waypoints within the terminal maneuvering area, the area within 15 nm of the airport, are determined from the runways in use. The arrival route has a waypoint at the arrival runway threshold called the missed approach waypoint (MAWP). Following the route in reverse, there is a final approach waypoint (FAWP) on the final approach course five miles from the MAWP. The intermediate waypoint (IWP) is located ten miles from the MAWP along the final approach course. The base leg segment is perpendicular to the final approach segment of the route. Base leg turn waypoints (BLTWP) are located on each side of the final approach course 5 miles from the IWP. The remaining arrival waypoint is located on each downwind leg of the approach at the intersection of the downwind leg and a line connecting the low altitude arrival waypoint and the center of the terminal area. It is called the downwind leg turn waypoint (DLTWP).

One remaining waypoint for use by departures is the departure waypoint (DWP) located on the runway heading, five miles from the center of the airport. Departing aircraft proceed directly from the DWP to the low altitude departure waypoint. Aircraft departing in the direction of the final approach heading must execute a 180° turn in order to proceed to the low altitude departure waypoint. A diagram of a completed terminal area design is shown in Figure 3.8. Examples of the standard terminal design concept applied to Philadelphia are shown in Figure 3.9 and 3.10.

3.4.4.4 Waypoint Locations for the Non-Primary Runway

An important aspect of the standard terminal area design is the fact that when the landing and/or departure runway are changed from the primary IFR landing runway, only the waypoints in the terminal maneuvering area are affected. The transition area waypoints remain unchanged. The location of the DWP, MAWP, IWP, and the BLTWP become aligned with the new active runway (or runways) in the same manner as described in Section 3.2.3. The route segments from the low altitude arrival waypoints go directly to the BLTWP or to the IWP unless a downwind leg is required. Similarly the departure traffic proceeds directly from the DWP to the LADWP, which has remained in a fixed geographic location. An example of how the transition area waypoints remain fixed while the terminal maneuvering waypoints move to the new active runway is shown in Figure 3.11. In this example the active runway is located at a 45° angle with respect to the primary runway on which the basic design was constructed (Figure 3.8). It can be noted that the DWP, MAWP, and BLTWP are located in the same relative position to runway 05 as they were to runway 36 in Figure 3.8. Note also that the transition area waypoints HAAWP, HADWP, LAAWP, LADWP and LAEWP are in exactly the same position in both Figures 3.8 and 3.11. Only the terminal maneuvering area waypoints have changed.

LAEWP	Low Altitude Enroute Waypoint	BLTWP	Base Leg Turn Waypoint
HAAWP	High Altitude Arrival Waypoint	IWP	Intermediate Waypoint
HADWP	High Altitude Departure Waypoint	DWP	Departure Waypoint
LAAWP	Low Altitude Arrival Waypoint	FAWP	Final Approach Waypoint
LADWP	Low Altitude Departure Waypoint	MAWP	Missed Approach Waypoint
DLTWP	Downwind Leg Turn Waypoint	➤	Direction of Traffic Flow



Low Altitude Transition Route

TMA and High Altitude Routes

Octant Boundary

Figure 3.8 Task Force Terminal Area Design

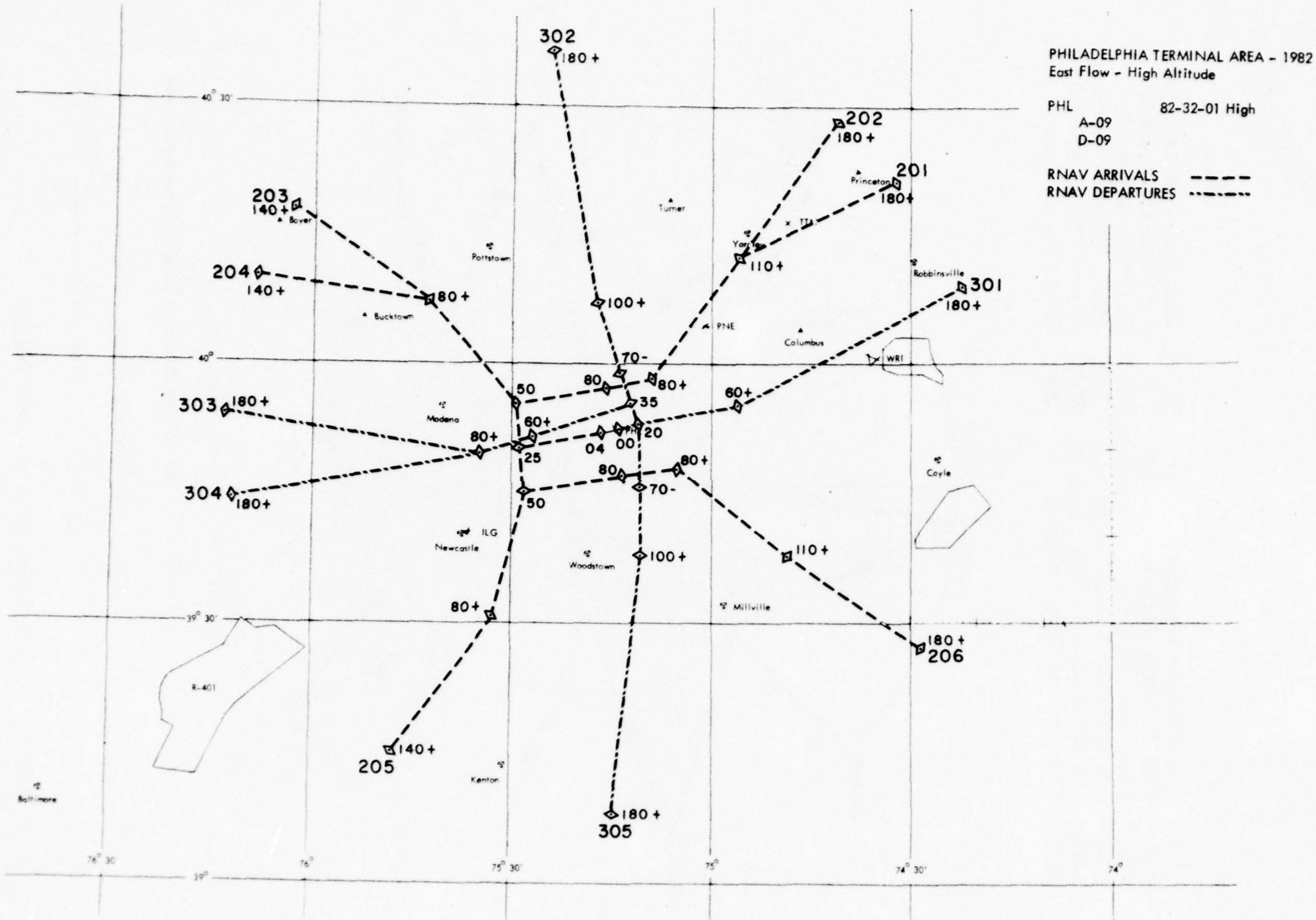


Figure 3.9 Philadelphia Terminal Area - High Altitude Routes

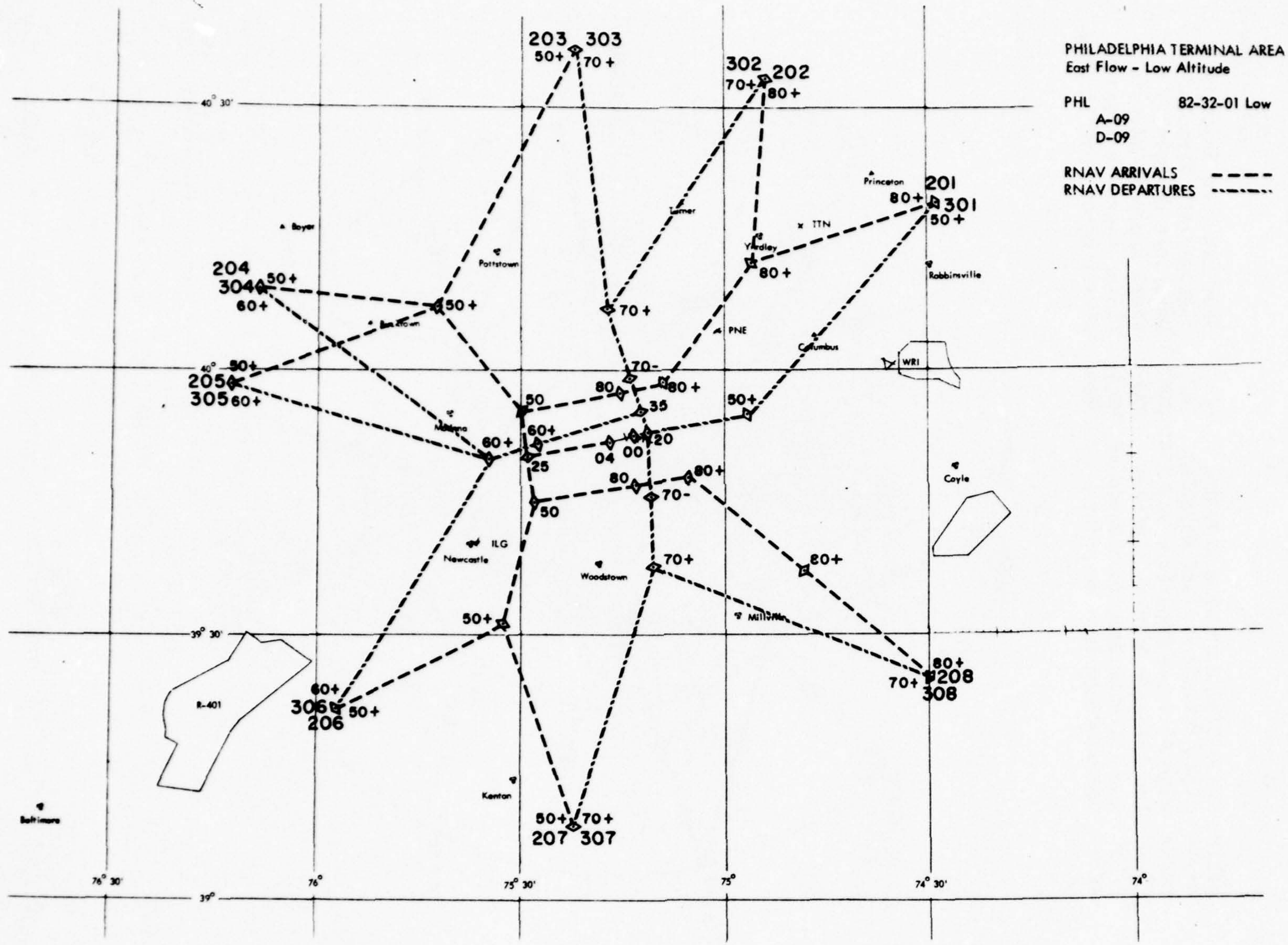


Figure 3.10 Philadelphia Terminal Area - Low Altitude Routes

LAEWP	Low Altitude Enroute Waypoint	BLTWP	Base Leg Turn Waypoint
HAAWP	High Altitude Arrival Waypoint	IWP	Intermediate Waypoint
HADWP	High Altitude Departure Waypoint	DWP	Departure Waypoint
LAAWP	Low Altitude Arrival Waypoint	FAWP	Final Approach Waypoint
LADWP	Low Altitude Departure Waypoint	MAWP	Missed Approach Waypoint
DLTWP	Downwind Leg Turn Waypoint	➤	Direction of Traffic Flow

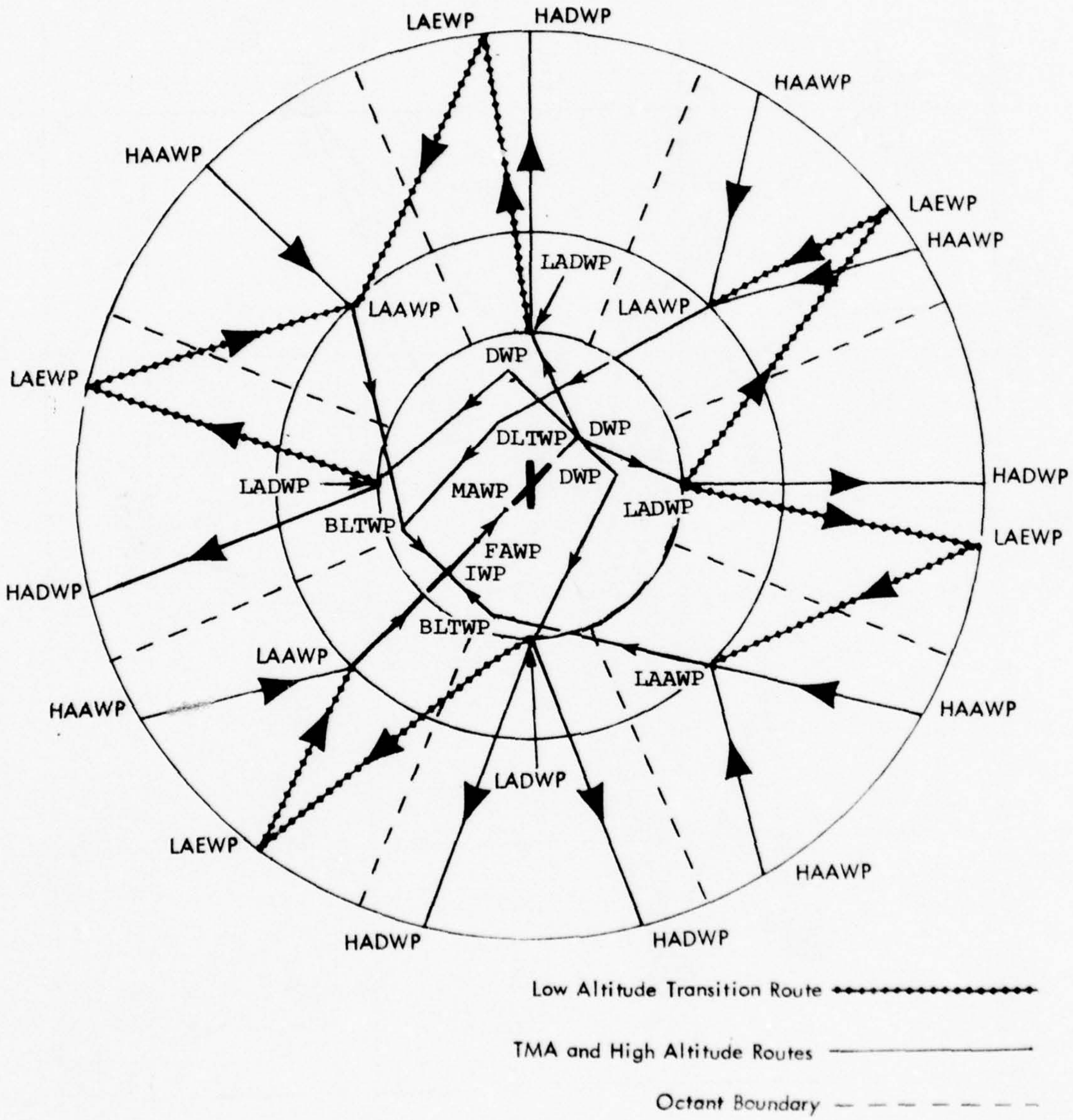


Figure 3.11 Task Force Terminal Area Design Applied to a Non-Primary Runway

3.4.4.5 Holding Airspace

Holding pattern airspace can easily be incorporated at the low altitude arrival waypoint. An example of the design of holding pattern airspace is shown for New Orleans in Figure 3.12. Number 10 holding pattern templates were used in this example to accommodate aircraft from 7,000-14,000 feet in the pattern.

3.4.5 Waypoint Altitudes and Route Widths

The Air Transport Association [4] recommended climb gradients of 400 feet/mile and descent gradients of 300 feet/mile, which were adopted by the Task Force. These values were used in the initial terminal designs with a slight modification for altitudes above 10,000 feet during climbs. Above this altitude level the aircraft climb gradient decreases for two reasons. First, the higher airspeeds utilized in this area result in lower climb rates and, second, the available engine thrust is decreasing due to the reduced ambient air density at these altitudes. To account for this effect, aircraft climb gradients were reduced to 300 feet/mile from 10,000 to 18,000 feet and to 200 feet/mile above 18,000 feet.

Routes in the transition area that were clear of all crossing route situations were often given unrestricted altitude ceiling constraints. For example if a departure had to clear 5,000 feet at some point in order to top an arrival route, and no further crossing route constraints were encountered before the aircraft exited the terminal area, the altitude restriction at that point was designated as 50+ meaning that the aircraft could be at or above 5,000 feet MSL upon crossing the point in question. If no altitude restrictions were encountered anywhere along the route, the waypoint altitudes were specified as 5,000 feet AGL or above in most cases. Separation between crossing 2D RNAV routes was maintained at the present operational value of 1,000 feet. RNAV route widths for the 1977-82 and post-1982 periods were narrowed from the present terminal area value of $\pm$ 2 nm to $\pm$ 1.5 nm as recommended by the TASK Force Report [1]. However, the terminal area designs in most cases would be unaffected if route widths of $\pm$ 2 nm were used out to 25 nm from the center of the terminal area.

3.5 THE TASK FORCE 3D (VNAV) TERMINAL AREA MODEL

The VNAV Task Force terminal area model was designed to be an evolutionary development of the 2D RNAV terminal area model. In this regard the Task Force RNAV terminal area model becomes the basis for the VNAV design.

The development of a VNAV terminal design brings to light several problem areas that are not encountered in conventional VOR and RNAV terminal area designs. These problems include:

1. Specification of VNAV profile type
2. Selection of vertical gradients
3. Separation of VNAV routes, particularly in the vertical direction
4. Accommodation of multiple enroute altitudes
5. Consideration of horizontal and vertical offset paths

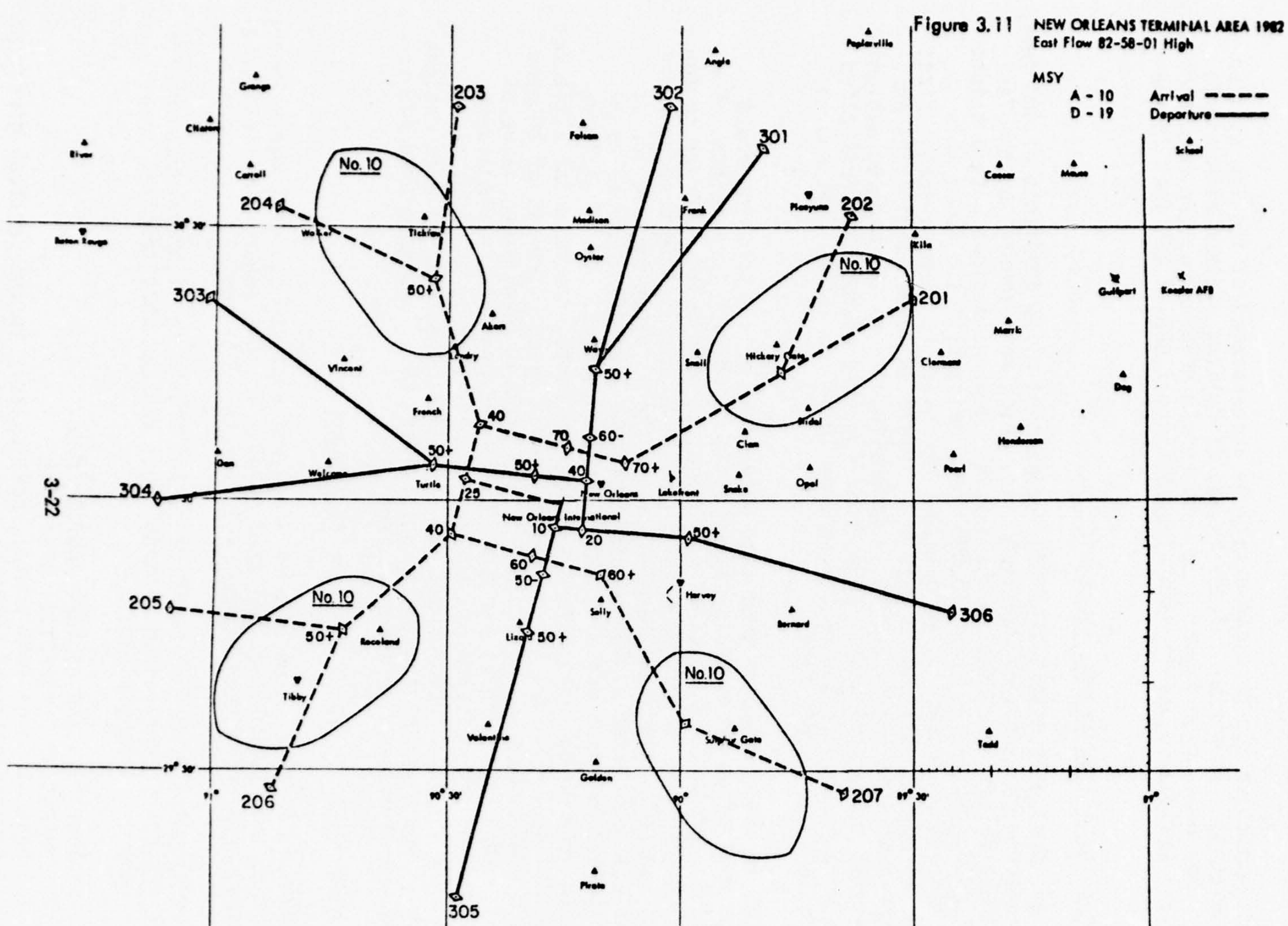


Figure 3.12 New Orleans Terminal Area Routes with Holding Airspace

Two types of VNAV profiles were considered as potential candidates for the VNAV routes. The first is the VNAV profile which utilizes specified altitudes at each of the waypoints. The specified altitude profile (SAP) is shown in Figure 3.13. The specified altitude profile can be flown by all types of VNAV equipment which meet the operational requirements of RTCA document DO-152 [5]. The SAP also permits lower performance aircraft to fly at shallower gradients than the specified gradient profile (SGP). The SGP, shown in Figure 3.14, has level cruise segments which intercept a specified gradient, and keeps aircraft at their cruise altitude for a longer period of time than does the SAP. The SGP has slightly higher airspace utilization than does the SAP because many routes cross at a zero gradient value rather than in climbing or descending flight. However, SGP's are slightly more demanding from a VNAV equipment standpoint. The SGP profile can be flown only by VNAV equipment which has constant gradient input capabilities or along track offset capabilities. The SAP type of design was selected as the design model because of its equipment compatibility characteristics and its ability to accommodate the lower performance aircraft.

3.5.1 VNAV Gradients

The selection of the maximum gradient is a very complex problem in the VNAV route design task. Aircraft climb gradients are affected by several factors including aircraft type, winds, air temperature, aircraft gross weight and aircraft speed. In some preliminary work on VNAV profiles in the terminal area reported in Reference 4, gradients of 400 ft/nm in climbs to 18,000 ft and 300 ft/nm in descent were used. These were based on the performance of an "average" Boeing 727 aircraft. In reviewing some aircraft profiles for the DC8, DC9 and DC10 [6,7,8] it was found the 300 ft/nm descent is generally compatible with conventional high speed descents. However, the climb gradient of 400 ft/nm seemed optimistic for aircraft above 10,000 ft, particularly for heavy aircraft on hot days with tailwinds. Based on these performance handbooks the following maximum gradients were adopted.

Climb = 400 ft/nm up to 10,000 ft
300 ft/nm between 10,000 and 18,000 ft
200 ft/nm above 18,000 ft
Descent = 300 ft/nm at all altitudes

3.5.2 VNAV Route Separation

VNAV route separation criteria have not yet been established. Consequently, based upon the lateral and vertical equipment accuracy figures for 1982 in the FAA/Industry RNAV Task Force Report [1] and the separation equations of Appendix A, the following minimum separation equation for vertical route centerlines was established.

$$S = V_1 + V_2 + B + L_1 \left| \frac{\tan \beta_2 - \cos \theta \tan \beta_1}{\sin \theta} \right| + L_2 \left| \frac{\tan \beta_1 - \cos \theta \tan \beta_2}{\sin \theta} \right| \quad \text{(Equation 1)}$$

where S = Minimum VNAV route separation value at the route centerlines

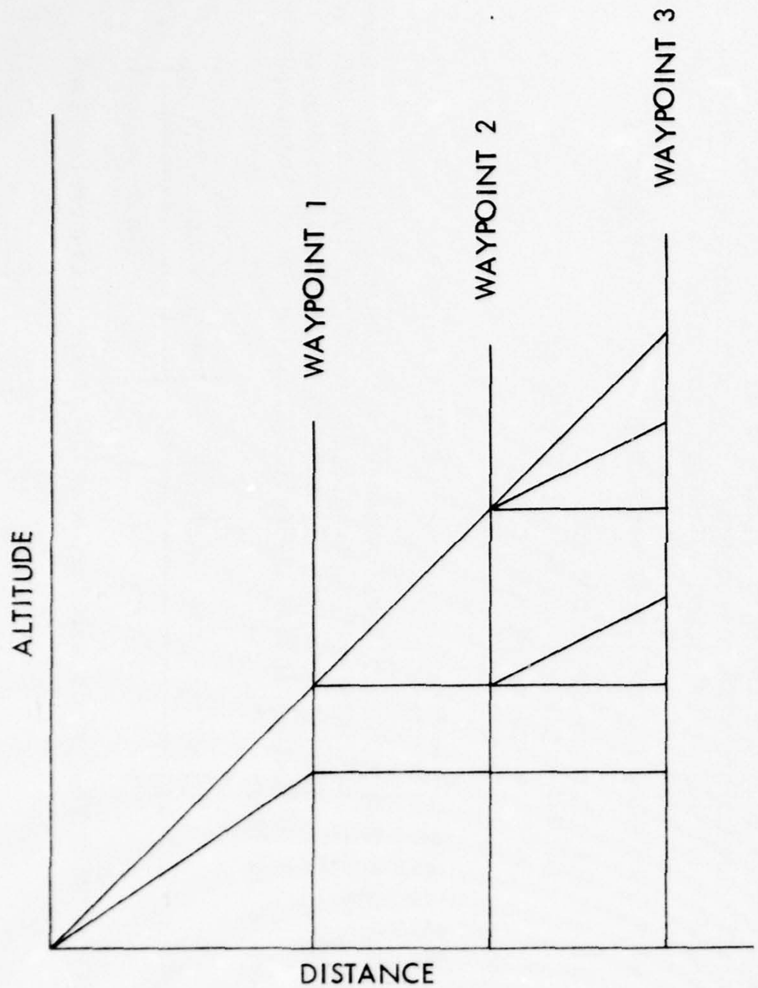


Figure 3.13 VNAV Profile With Specified Altitudes at Each Waypoint (SAP)

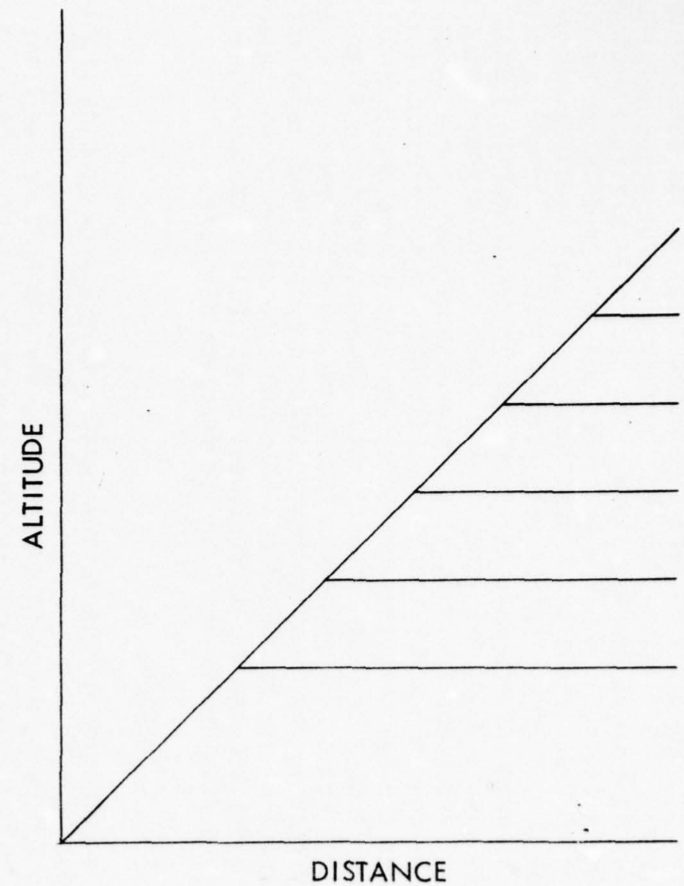


Figure 3.14 VNAV Profile with Level Cruise Segments to a Specified Gradient (SGP)

$V_{1,2}$ = Vertical half tube dimension for route 1,2

$L_{1,2}$ = Lateral half tube dimension for route 1,2 = 9114 ft. for the terminal area (± 1.5nm)

B = Airspace buffer zone value = 300 ft.

$\beta_{1,2}$ = Vertical path angle for route 1,2

θ = Intersection angle of routes in the horizontal plane

The vertical half tube size can be expressed as

$$V = \sqrt{(V_o)^2 + (V_{at} \cdot \beta_{1,2})^2}$$

where V_o = 350 ft.

V_{at} = 180 feet/degree of vertical path angle

$\beta_{1,2}$ = Vertical path angle (degrees)

The geometrical aspects of this separation equation are difficult to depict due to the three dimensional aspects of the VNAV separation problem. However, four specific examples of special cases are presented to demonstrate the separation relationships.

<u>Example 1</u>

Let the intersection angle between the two routes go to zero. In this situation the two VNAV route centerlines fall in the same vertical plane. Certainly, if the gradients are not of the same value the routes must intersect at some point. Consequently, a minimum separation value is undefined or infinite.

Examination of the separation equation shows that for small values of the angle θ and β_1 β_2 the equation can be expressed as

$$S = V_1 + V_2 + B + \frac{L_1}{\sin\theta} (\tan\beta_2 - \cos\theta \tan\beta_1) + \frac{L_2}{\sin\theta}(\tan\beta_2 \cos\theta - \tan\beta_1)$$

The terms containing L_1 and L_2 become infinite as θ goes to zero except under special circumstances which will be discussed in Example 2. Consequently, the separation value S becomes infinite, as predicted by the analysis.

<u>Example 2</u>

Consider the previous example but let the vertical path angle be the same in both VNAV routes. Under these circumstances it would be expected that the minimum route separation value would be

$$S = V_1 + V_2 + B$$

This can readily be confirmed by examining Figure 3.15.

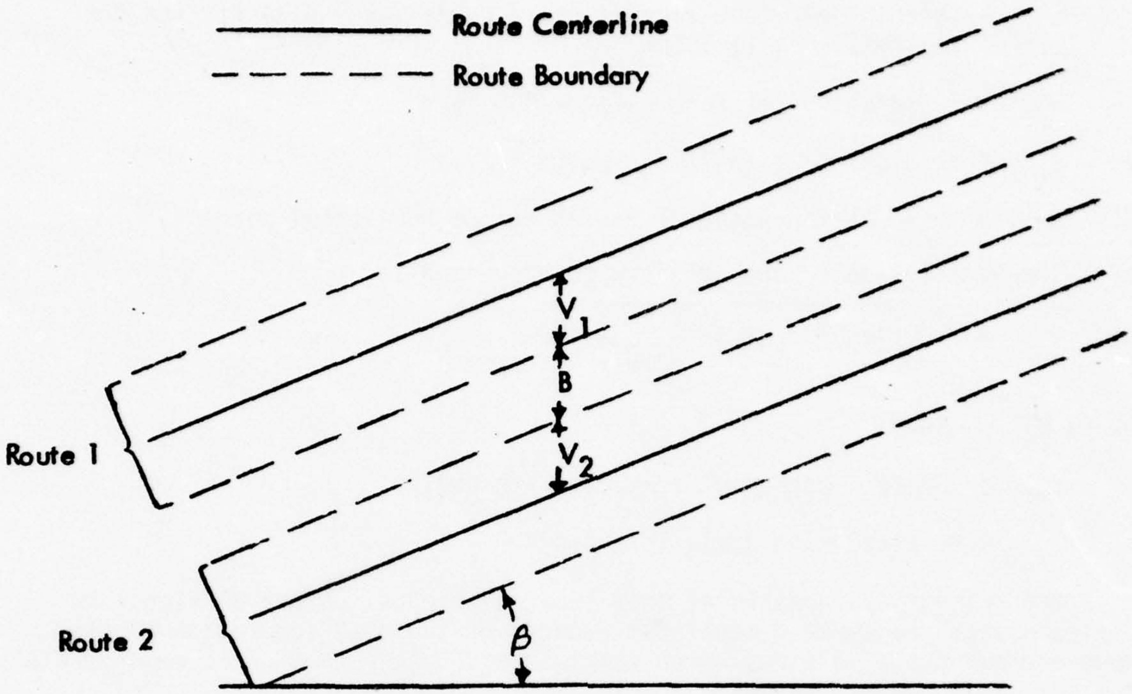


Figure 3.15 Separation of VNAV Routes Having Equal Gradients

Consider the separation equation for equal flight path angles $\beta_1 = \beta_2 = \beta$.

$$S = V_1 + V_2 + B + L_1 \tan\beta \left(\frac{1-\cos\theta}{\sin\theta} \right) + L_2 \tan\beta \left(\frac{\cos\theta - 1}{\sin\theta} \right)$$

In order to check the behavior of the L_1 and L_2 terms as θ goes to zero, an application of L'Hospitals' rule may be applied since both the numerator and the demoninator go to zero.

Consequently

$$\lim_{\theta \to 0} \left\{ \frac{1-\cos\theta}{\sin\theta} \right\} = \lim_{\theta \to 0} \frac{\frac{d}{d\theta}(1-\cos\theta)}{\frac{d}{d\theta}(\sin\theta)} = \lim_{\theta \to 0} \frac{\sin\theta}{\cos\theta} = 0$$

or

$$S = V_1 + V_2 + B$$ as shown in Figure 3.15

Example 3

Let the vertical gradients β_1 and β_2 go to zero. This situation is depicted in Figure 3.16. The routes now lie entirely in the horizontal plane and the separation value should be the 1000 ft that is in current use in the 2D VOR and RNAV route structures. This separation value is independent of intersection angle.

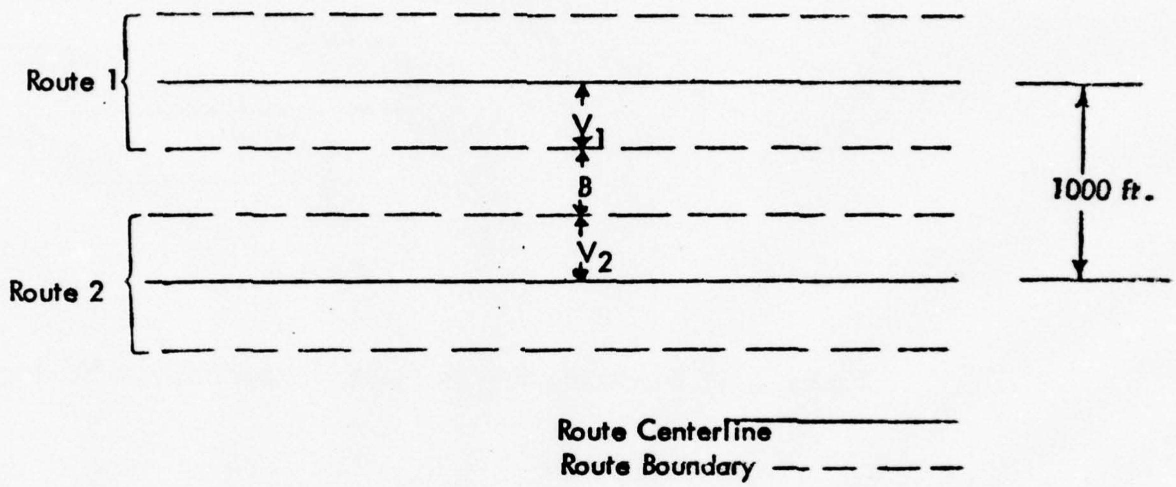


Figure 3.16 Separation of VNAV Routes with Zero Vertical Path Angle

Using values of zero degrees for β_1 and β_2 and 300 feet for B it is apparent that $V_1 = V_2$=350 ft. Therefore

$$S = 350 + 350 + 300 = 1000 \text{ ft.}$$

Example 4

In this example let the VNAV routes cross at an angle of 90° and let the angle $\beta_2 = 0°$. This situation is shown in Figure 3.17.

From the diagram it can be observed that

$$S = V_1 + V_2 + B + L_2 \tan \beta_1$$

Examination of Equation 1 for $\theta = 90°$ and $\beta_2 = 0$ provides the identical results.

Several curves depicting the minimum separation values from Equation 1 are presented in Figure 3.18. Curves for several values of vertical path angle gradients are shown. An example is shown in Figure 3.18 where $\beta_1 = 4°$, $\beta_2 = 3°$, and $\theta = 100°$. The resultant vertical separation required between route centerlines is 3050 feet.

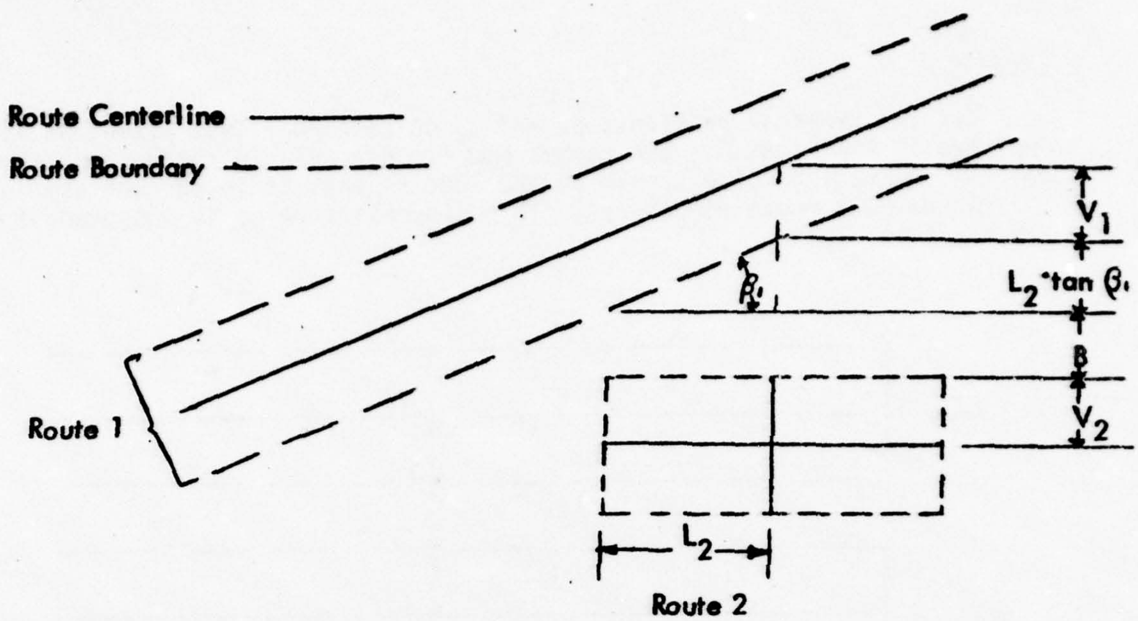


Figure 3.17 Separation of VNAV Routes Intersecting at a 90° Angle

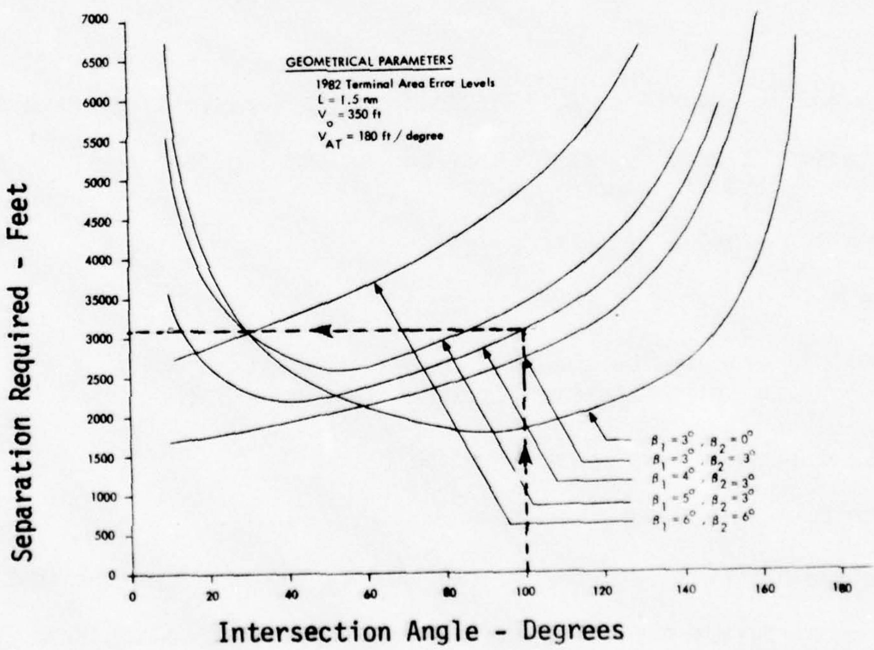


Figure 3.18 Minimum Separation Values for Terminal Area VNAV Routes

3.5.3 VNAV/RNAV Route Separation

The separation of 3D-VNAV route from 2D-RNAV or VOR routes can be determined from the separation equation discussed in the previous section. Since the 2D route has no gradient value, the separation can be computed by setting the angle β of the 2D RNAV or VOR route equal to zero. Consequently, if route 2 in the separation equation is the RNAV route the separation for terminal area 2D/3D route crossings becomes

$$S = V_1 + V_o + B + L_1 \left| \frac{\cos\theta \tan\beta_1}{\sin\theta} \right| + L_2 \left| \frac{\tan\beta_1}{\sin\theta} \right|$$

where

$$V_1 = \sqrt{(V_o)^2 + V_{at} \cdot \beta_1}$$

V_o = 350 ft

V_{at} = 180 ft/degree of vertical path angle

β_1 = vertical path angle for the VNAV route (route 1)

L_1 = route width of the VNAV route at the crossing point

L_2 = route width of the RNAV route at the crossing point

B = airspace buffer area = 300 feet

The curve in Figure 3.18 depicting the (β_1 = 0° and β_2 = 3°) gradient values can be applied to a 3° VNAV route which crosses an RNAV route or a VOR route with a ± 1.5 nm route width value.

3.5.4 VNAV Design Approach

The terminal designs using VNAV Task Force profiles were developed by using a combination of the plan view and profile view of each route. The design process is outlined below.

1. Develop plan and profile views for each route in the terminal area. The plan view was taken from the Task Force 2D RNAV terminal design model. The profile views were developed according to the gradients discussed earlier in this section.

2. Identify all route crossings on the plan view and display on the profile view at the appropriate flight path distance and altitude. Resolve conflict situations by lowering VNAV profiles or moving routes on the plan view.

3. Develop VNAV routes on the profile view for altitudes below the specified gradients for each route and display the crossing altitudes on those affected profile views. Resolve conflict situations.

4. Create waypoints at route turn points and at other points which help expedite the flow of VNAV traffic. In order to minimize pilot workload a minimum number of waypoints were used. Also waypoints were spaced at least 10 nm apart unless it was necessary from a conflict resolution standpoint or a turning point standpoint to locate them closer than 10 nm.

5. Resolve all conflict situations using standard gradients or a less than standard gradient.

3.6 APPLICATION OF THE TASK FORCE MODEL

The Task Force model was applied for each of the three time periods with varying degrees of modification as described in the following paragraphs.

3.6.1 1972-1977 Transition Period Application

In general, the 1972-77 designs are patterned after the current radar vector/VOR routes. New RNAV routes are incorporated if they meet the following criteria:

1. The route will serve a traffic demand area.
2. The route does not violate the octant flow pattern.
3. Waypoint locations can be made compatible with current flow patterns.

These criteria recognize the goal of the final design based upon the octant pattern but yet utilize the radar vector routes of the current terminal area designs to minimize conflict with existing traffic flows. Also, the development of new routes is based upon the requirements of the airspace users. New routes are not added unless there is a user requirement for those routes. In some terminal areas these criteria led to the development of several new RNAV routes in the 1972 designs, while other terminals have no new independent routes but only RNAV routes

which overlie conventional routes. The differences between specific 1972 designs from this aspect is generally due to two factors. First, the consistency of the terminal area with the octant flow pattern will affect the development of new routes. In those terminals where the octant pattern is violated over much of the airspace, very few, if any, RNAV routes can be located where they either do not violate the octant flow or where they do not interfere with present radar vector routes. The second reason that few RNAV routes may be developed in some terminals in the 1972 design is that the conventional routes are currently designed to handle the major traffic flows, and the addition of new routes would tend to clutter the airspace without necessarily providing any operational benefit to the user or to ATC. This situation often occurs in high density traffic areas such as New York.

3.6.2 1977-1982 Transition Period Application

The 1977-82 design gives considerably more weight to the octant flow pattern than does the 1972-77 design. The post-1982 terminal area designs were constructed prior to the development of the 1977-82 route structures. The 1977-82 designs were developed from the post-1982 designs with the VOR route constraints applied. This design sequence provided assurance that the 1977-82 designs and the post-1982 designs were consistent. In situations where the octant flow pattern is violated by the 1972-77 design, the conventional route is moved to be in closer harmony to the octant pattern. The location of current navigation facilities will affect the relocation of the conventional routes so that the conventional traffic can operate to a point within 20-25 nm of the airport on VOR radials. Inside of this distance, radar vectors are presumed. Wherever possible, current intersections and fixes are used in order to minimize the need to develop new arrival or departure procedures. In the 1977-82 design it is now possible and desirable to develop one or more RNAV routes for each octant depending on traffic demand. In some cases, the RNAV routes will still overlie the conventional routes.

In many ways the 1977-82 design concept is the most difficult. The major problem that exists in these designs is that both RNAV and conventional traffic must be accommodated. The philosophy that was adopted on this point was to provide the RNAV user with routes that will be operationally satisfactory, in that there are as few altitude restrictions as possible and that the routes are not excessive in length. However, the necessity to also provide for the conventional traffic creates a situation whereby the airspace appears very cluttered and congested, especially in areas like New York.

As the design of the seven 1977-82 terminal areas progressed, it was recognized that the accommodation of both VOR and RNAV routes within the terminal maneuvering area was not feasible from an airspace congestion standpoint. Consequently, a different technique was applied in the terminal area designs for the Miami and San Francisco areas. The 1982 terminal routes were utilized in the 1977-82 designs inside of the low altitude arrival and departure waypoints. Conventionally equipped arrival aircraft are vectored to the final approach course while conventional departures are vectored until they can receive the appropriate departure VOR radial. Conventional aircraft

use the VORTAC system for navigation in the terminal transition area. Occasionally this design technique could create the need to move a low altitude arrival or departure waypoint in order to create a VOR intersection at the same location. This situation was not encountered in Miami or San Francisco, however.

3.6.3 Post-1982 Application

Wherever possible the post-1982 design is based directly on the Task Force model. The factors which may cause the design to depart from the Task Force model are:

1. Multiple major airports in terminal area.
2. Satellite airport traffic patterns that cannot be altered.
3. Multiple runway configurations at the terminal airport.
4. Terrain features in the terminal areas.
5. Noise abatement or other special requirements.
6. Presence of another major terminal nearby (e.g. New York - Philadelphia).

A skeleton conventional route structure for low altitude traffic is retained in 1982. This route structure is set up to use current VOR facilities to arrive or depart from the RNAV low altitude arrival and departure waypoints. In addition to those caused by the above listed factors, the following minor changes to the Task Force model were made:

- Low altitude waypoints were moved 3 miles to more nearly conform to existing feeder fixes.
- The airport departure waypoint was replaced by departure waypoints located 5 miles away along runway heading.
- The concept of 45 mile circles around major airports in a metroplex, which in turn are included in a larger circle, was found to be unworkable. Instead a circle which enclosed all existing feeder fixes was found to provide an acceptable terminal area boundary.

3.6.4 Design Descriptions

Descriptions of the initial terminal area designs resulting from the application of the Task Force Model are given in Sections 5, 6, and 7 for the 1972-1977, 1977-1982, and post-1982 periods, respectively.

4.0 DESIGN ANALYSIS AND DEVELOPMENT OF FINAL DESIGN APPROACH

4.1 ANALYSIS OF 2D DESIGNS

The RNAV terminal designs that were developed during the study were analyzed from both a user and controller viewpoint in order to determine the benefits that would accrue to each, to assess the capability of the pilot and controller to operate in a mixed VOR/RNAV environment, and to evaluate the Task Force terminal area design concept. The primary issue that was addressed in the analysis of the transition time periods (1972-1977 and the 1977-1982 terminal area designs) was the ability of the ATC system and specifically the air traffic controller to handle aircraft in a mixed RNAV and radar vector/VOR environment. On the other hand the issue that was considered important in the post-1982 time period was the question of whether the post-1982 RNAV terminal area designs provided economic benefits to the airspace user without adverse effect on the ATC system.

4.1.1 Impact on ATC System

In order to investigate the effect of RNAV terminal area operations upon the air traffic control system, real time simulations of the New York terminal area were performed at NAFEC [13, 18]. Terminal area route structures for all three time periods were simulated for the southwest flow (Runway 22) operations at John F. Kennedy International Airport. In the two transition period simulations involving the 1972-1977 and 1977-1982 route structures, departure traffic from La Guardia, Newark, Islip and Republic,and arrival traffic to Islip and Republic were included in the simulation in order to provide realistic traffic levels for all Kennedy controller positions. In the post-1982 time period simulation only the Kennedy traffic was simulated. However, increased Kennedy traffic levels were used during this simulation in order to examine ATC system capacity effects with various RNAV and VNAV participation levels.

In the transition period simulations several levels of RNAV-VOR/radar vector mix were simulated in order to investigate the effect of increasing the RNAV traffic on the route structures of the two time periods. The traffic level and traffic type populations remained the same for all time periods and RNAV-VOR percentages; however, the selection of when a specific aircraft was to enter the simulation problem was made on a random basis from the traffic populations. In the 1972-1977 route structure RNAV percentages of 0%, 25%, 50% and 75% were used and in the 1977-1982 route structure RNAV percentages of 25%, 50%, 75% and 100% were simulated. In addition, 5 controller teams were used in each of the two time periods. Thus, a total of 20 simulation data runs were performed for each of the two transition time periods. An extensive number of data parameters were recorded during the simulation runs, including traffic sample data, route and altitude data, delay times, and controller workload data.

In the post-1982 period simulation various VOR-radar vector, RNAV and VNAV participation levels were simulated. Table 4.1 summarizes the various combinations of participation levels that were considered. There were four controller teams used in the simulation.

TABLE 4.1 **Number of Test Runs-By Participation Levels [18]**

Percentage of RNAV Traffic \ Percentage of VNAV Traffic	0	25	50	75	100
100	4				
75	4	4			
50	4	4	4		
25	4	4	4	4	
0	4	4	4	4	4

Note: The balance of the traffic in each cell needed to bring the total to 100 percent is radar-vectored traffic.

Each controller team completed all of the 15 test conditions that are shown in Table 4.1. The conditions of this post-1982 simulation were set up such that terminal area capacity comparisons could be made for each of the 15 RNAV-VNAV participation levels. In addition, data pertaining to controller workload and aircraft flight path characteristics were recorded.

Each data parameter that could potentially indicate an influence of RNAV on the terminal design and controller traffic handling ability was processed by a regression analysis to produce trend-line data as a function of RNAV percentage traffic. The trend-line data were then used to determine the impact of RNAV procedures in the terminal area upon the controller and upon system capacity.

4.1.2 Impact on Airspace User

Some measure of the quality of the terminal area design produced during this investigation was necessary in order to determine if the RNAV designs produced a benefit for the user. The technique used for evaluating this benefit was to quantify the time and fuel improvements of several aircraft types operating over the RNAV designed route structure for 1982 as compared to the current 1972 radar vector/VOR route structure [3]. The performance characteristics of four air carrier turbojet aircraft were selected for the analysis in the initial design effort. These aircraft are:

McDonnell Douglas DC-9	Boeing 727
McDonnell Douglas DC-8	Boeing 747

In the final design effort four additional aircraft were considered in the analysis. These aircraft are representative of three engine wide-body jet aircraft, business jet aircraft and commercial turboprop aircraft. The aircraft selected for analysis are:

McDonnell Douglas DC-10	Fokker F.28
Learjet 25	Fairchild Hiller FH227D

Standard handbook climb and descent data for these aircraft were used to compute the amount of time and fuel used on each design route. The aircraft were permitted to climb or descend at their handbook values unless an altitude restriction was encountered. When restrictions were encountered, the aircraft was assumed to fly level after achieving the assigned altitude until a point was reached such that the restriction was changed or removed.

Traffic was apportioned to each route in the terminal area by using data on city pair traffic from the 1971 peak day IFR records [9]. Traffic used the arrival or departure route that most closely matched the great circle heading between the city pair. Time and fuel benefits were then computed by comparing the RNAV terminal designs (for 1982) with the radar/VOR terminal designs for 1972-1977.

4.2 VNAV ANALYSIS

The Task Force recommendations for the introduction of VNAV are predicated upon the hypothesis that 3D procedures will improve airspace utilization and will benefit both the ATC system and the users of the airspace. This hypothesis was examined, for terminal area operations, from both the operational and economic viewpoint, and the results utilized in the development of recommended terminal area design guidelines. The issues concerning VNAV implementation are as follows:

- ATC procedures
- Airspace design criteria
- Avionics and pilotage considerations
- VNAV economic impact

Avionics and pilotage requirements have been documented in "Minimum Operational Characteristics for Vertical Guidance Equipment Used in Airborne Volumetric Systems", DO 152 [5], published by the RTCA SC-116E committee, and are discussed further in Appendix A.

4.2.1 Route Separation and Procedural Effects

Vertical flight path control through the use of fixed gradient 3D area navigation (VNAV) computers as recommended by the Task Force would produce a profound change in the manner by which aircraft are controlled - both from the cockpit and the air traffic control standpoint. Today the air traffic controller handles IFR aircraft in the vertical dimension by issuing clearances from one altitude level to another. In the transition from one altitude to

another the pilot is generally free to choose the type of flight profile which best suits the performance characteristics of his aircraft. Thus the vertical flight path history of an aircraft under IFR circumstances consists of level altitude segments separated by transition segments which vary from aircraft to aircraft and pilot to pilot.

The use of fixed gradient VNAV routes would change this situation by requiring the pilot to maintain a specified trajectory in the altitude transition regions of his flight path. By requiring the aircraft to maintain these profiles, the uncertainty in the aircraft's position is reduced during altitude transitions. This reduced uncertainty in position will in theory reduce the amount of airspace that is required for that route, thus permitting airspace designers to put more routes in a given volume of airspace. However, as the analysis in Appendix A illustrates, the amount of usable airspace which can be gained is minimal. VNAV separation requirements are presented in detail in Appendix A, and the results as applied to terminal area design are discussed Section 7.3.2.

The impact of VNAV airspace design and operations upon current airspace sectorization techniques, ATC control procedures, display equipment and ATC automation levels is discussed in Appendix A.

4.2.2 Impact on Airspace User

Standard and VNAV climb and descent performance characteristics of typical jet aircraft were analyzed in order to assess the impact of fixed gradient VNAV procedures on time and fuel consumption parameters. The climb performance analysis compared the time and fuel required for VNAV climbs at various gradients as compared to a standard aircraft handbook climb for a DC-9, a DC-8 and a DC-10 aircraft. The descent analysis compares the time and fuel consumed in high speed RNAV and VNAV descents with the time and fuel consumed in a standard 250 knot descent for a DC-10 aircraft. The results of the VNAV climb and descent analysis are contained in Section 7.3.2.

4.3 DEVELOPMENT OF MODIFIED DESIGN GUIDELINES

The results of the altitude restriction/route length analysis described in Section 4.1.2 suggested that some modifications of the basic Task Force octant concept and the altitude profile development are necessary in order to improve aircraft time and fuel consumption. As a result a set of modified terminal area design guidelines was developed for the post-1982 period. The detailed development of these modified guidelines is decribed in Section 7.4 following the 2D and 3D analysis of the initial post-1982 designs in Sections 7.2 and 7.3. The modified guidelines were applied to the development of a modified post-1982 New York terminal area design, and the design was analyzed for impact on user benefits. The results of the analysis, described in Section 7.4.3, indicated significant improvements in fuel and time over the initial post-1982 New York design.

The modified design guidelines are based on the concept of utilizing vertical arrival and departure envelopes in which both 2D and 3D equipped aircraft may operate. The resulting designs provide optimum airspace utilization

and maximum economic benefits for both 2D and 3D equipped aircraft. The 3D equipped aircraft obtain additional benefits over the 2D equipped aircraft through use of pilot selected 3D gradients within the vertical envelopes.

The modified design guidelines were based on the results of both ATC and user impact analyses, and were utilized in discussions with user groups and controllers in the development of the final recommended terminal area design guidelines.

4.4 DEVELOPMENT OF FINAL DESIGNS

In order to validate the modified terminal area design guidelines with respect to their impact on the ATC system, a comprehensive briefing was prepared which described the methodology and results of the study at that point in time. This briefing was given at six of the seven terminal areas involved in the design study. The Denver area was not visited due to schedule incompatibilities. At each of the terminal areas that was visited, controller comments were nearly unanimous in support of the modified design concept over the strict application of the Task Force octant concept. In most of the terminal areas a majority of the controllers advanced the opinion that it would be difficult to operationally implement the original 1982 RNAV Task Force-based route structures. The one exception was in the Chicago area, which is currently organized essentially in an octant pattern. However, even in Chicago some of the strict application guidelines are changed somewhat, particularly in the area of octant alignment with the primary IFR landing runway.

Both the controller comments and the user benefits indicated that route structures based on the modified design guidelines could potentially provide more optimum route structures in the terminal area than could designs based on a strict application of Task Force design guidelines. In order to substantiate this hypothesis, a new design effort was initiated for two traffic flows in each of the terminal areas. First, the 1972 terminal designs were changed to be more representative of the 1972 VOR/radar vector procedures used at each of the terminals. These modifications are described for each design in Section 5. No specific RNAV routes were developed for these 1972 route structures. The primary purpose of developing these route structures was to provide a basis of comparison for the 1982 RNAV route structures and to identify compatible traffic flows in these two time periods. Hence, the development of independent RNAV routes for 1972 was not necessary to accomplish these two tasks.

Prior to the development of 1982 RNAV route structures, terminal design optimization programs were developed which identified candidate terminal area waypoint locations in a manner which would reflect user benefits based upon the traffic flow. Then a second data collection effort was initiated in order to obtain a more comprehensive sample of enroute traffic flow. The primary source of information for this data was the Official Airline Guide [15]. Then the waypoint location program using the new traffic sample was applied to each of the seven terminal areas. In addition, care was taken so as not to create route structures which produced excessive altitude restrictions for the aircraft.

Several combinations of arrival/departure sectors and waypoints per sector were used for each terminal area. The final waypoint configuration was selected independently for each terminal area and was based upon optimizing user benefits relative to traffic flow. In cases where one of the optimum combinations of arrival/departure sectors and waypoints corresponded generally with existing traffic flow, that combination was chosen in order to minimize implementation problems in the transition phases. This correspondence is particularly important in the early implementation stages of RNAV into the terminal area as it provides a means of achieving RNAV benefits to users at an early date. In areas with close correspondence between the RNAV design and the existing procedures it will be relatively easy to implement terminal RNAV route structures into the terminal operations. When these designs were completed, a user benefits analysis indicated that a significant user benefit could be obtained through the use of these designs.

A detailed description of the design procedures which were used, descriptions of the final post-1982 designs, and the results of the user benefit analysis are given in Section 7.

5.0 1972-1977 2D DESIGNS AND ANALYSIS

The Task Force design concepts for the 1972-1977 time period were applied to the seven terminal areas described in Section 3.2. In each of these seven terminals two runway configurations were selected for which RNAV route structures were developed. These structures are presented on maps of each of the seven terminal areas in the appropriate section of the report. The routes are shown as lines which are drawn between route end points or altitude restriction points. Each of these points is represented by a diamond figure (◊). The route turn points are necessarily RNAV waypoints. However, the altitude restriction points may be defined by DME distance from a waypoint and thus these points are not, of necessity, waypoints. Consequently, the diamond symbol (◊) should not necessarily be thought of as being a waypoint but rather a lateral or vertical control point which defines the route.

During the 1972-1977 time period the traffic in each of the terminals was assumed to be dominated by the radar vector/VOR traffic. In order to introduce RNAV procedures at each of these terminals with a minimum of implementation problems for both the controller and the pilot, the radar vector/VOR routes were considered as the basic route structure on which to build an RNAV route structure for this time period. Consequently the airport traffic patterns in the terminal maneuvering area and the departure gates and feeder fixes in the terminal transition area are determined by the current radar vector/VOR routes in use at the time that the terminal data was collected.

Independent RNAV routes in the terminal area are established in those areas where a user benefit such as a route length reduction or a more desirable altitude profile may be attained by the RNAV equipped aircraft. However, RNAV departure routes are not permitted to penetrate current arrival airspace sectors nor are RNAV arrival routes permitted to cross over present departure airspace during this initial RNAV transition time period.

In the Philadelphia 1972-77 design the RNAV routes and the radar vector/VOR routes are shown separately. In the other six terminal area designs, the RNAV routes and the radar vector/VOR routes are presumed to overlie one another and they are not depicted separately. In these six terminal area designs the two route structures are identical and the terms "1972-77 RNAV route structure" and "1972-77 radar vector/VOR route structure" can be used interchangeably.

An important part of the RNAV terminal area briefing that was given at six of the seven terminal areas was a validation of the 1972 VOR/radar vector route structures. For the most part there is a high degree of correspondence between these designs and the actual route structures utilized in current operations. However, some changes were necessary in all of the areas except New York. A description of these changes, along with a map of the amended route structure, is presented at the end of each terminal area description.

5.1 2D RNAV DESIGNS

This section describes the characteristics of the seven terminal areas for which designs were developed, and describes the RNAV route structures that were developed for the 1972-1977 RNAV implementation time period. Route structures

for thirteen airports in these seven terminal areas are presented. Two runway configurations are shown for each airport for a total of 26 designs for this time period.

5.1.1 New Orleans

5.1.1.1 Characteristics of the New Orleans Terminal Area

Airport Configuration

The New Orleans Terminal Area contains one major airport, New Orleans International (MSY), and two smaller airports which can accommodate IFR operations. The smaller airfields are New Orleans Lakefront Airport (NEW) and New Orleans Naval Air Station (NGB). The IFR traffic breakdown for these three airports as determined from peak day IFR data is as follows:

Airport	Total Operations	Low Departures	Low Arrivals	High Departures	High Arrivals
MSY	371	56	66	114	135
NEW	46	18	19	5	4
NBG	25	8	3	5	9

From these data it is quite apparent that the MSY traffic will dominate the traffic flow situation in the New Orleans Terminal Area. Consequently, the designs that were developed for New Orleans contained routes for traffic to and from MSY only.

Runway Orientation and Utilization

The physical characteristics of the MSY runways are shown in Figure 5.1. The primary runways 10-28 and 1-19 are oriented at 90° to each other and the shorter general aviation runway is aligned at a 45° angle to the primary runways. The primary IFR landing runway is Runway 10 which is aligned at a magnetic bearing of 100° or 106° true bearing. Runway 10 has Category II ILS capability. Runway 1 has an ILS approach procedure. The New Orleans TRACON personnel estimated that the approximate breakdown of runway utilization at MSY was as follows:

Utilization	Landing Runway	Departure Runway
40%	10	19
20%	10	01
20%	01	28
10%	28	28
10%	19	28

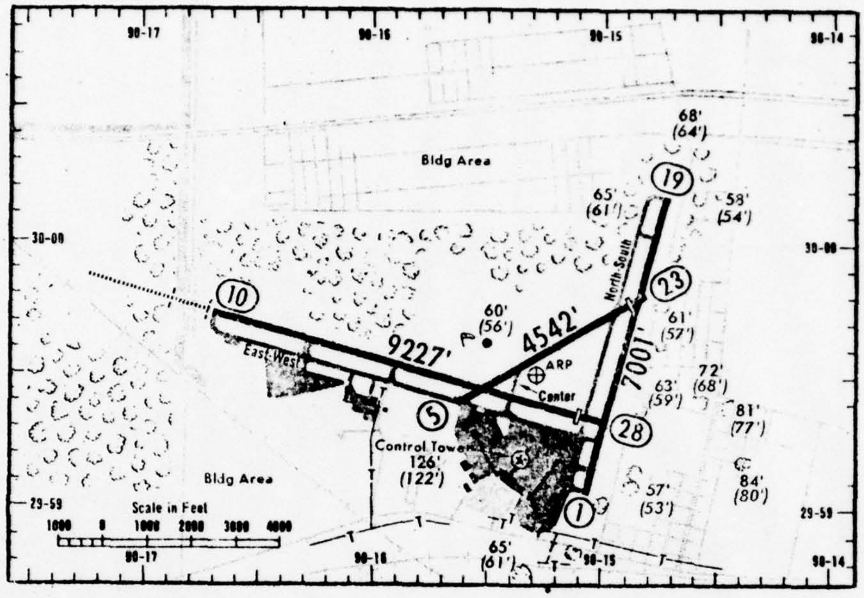


Figure 5.1 New Orleans Airport Configuration

In view of these utilization figures, the primary configuration selection for design consideration at MSY was -- Land-Runway 10/Depart-Runway 19. The secondary configuration selected was -- Land-Runway 01/Depart-Runway 28.

Terminal Area Traffic Flows

Current arrival and departure areas for the New Orleans TRACON are shown in Figure 5.2 and compared to the Task Force octant concept. The shaded areas are currently used arrival airspace areas and the unshaded regions are departure areas. On the periphery of the 30 nm range circle are shown the corresponding arrival and departure areas as conceived by the FAA/Industry Task Force Report. It is apparent from Figure 5.2 that the present New Orleans terminal design uses several more arrival and departure fixes than suggested by the Task Force Report, and that these fixes are not generally well aligned with the arrival

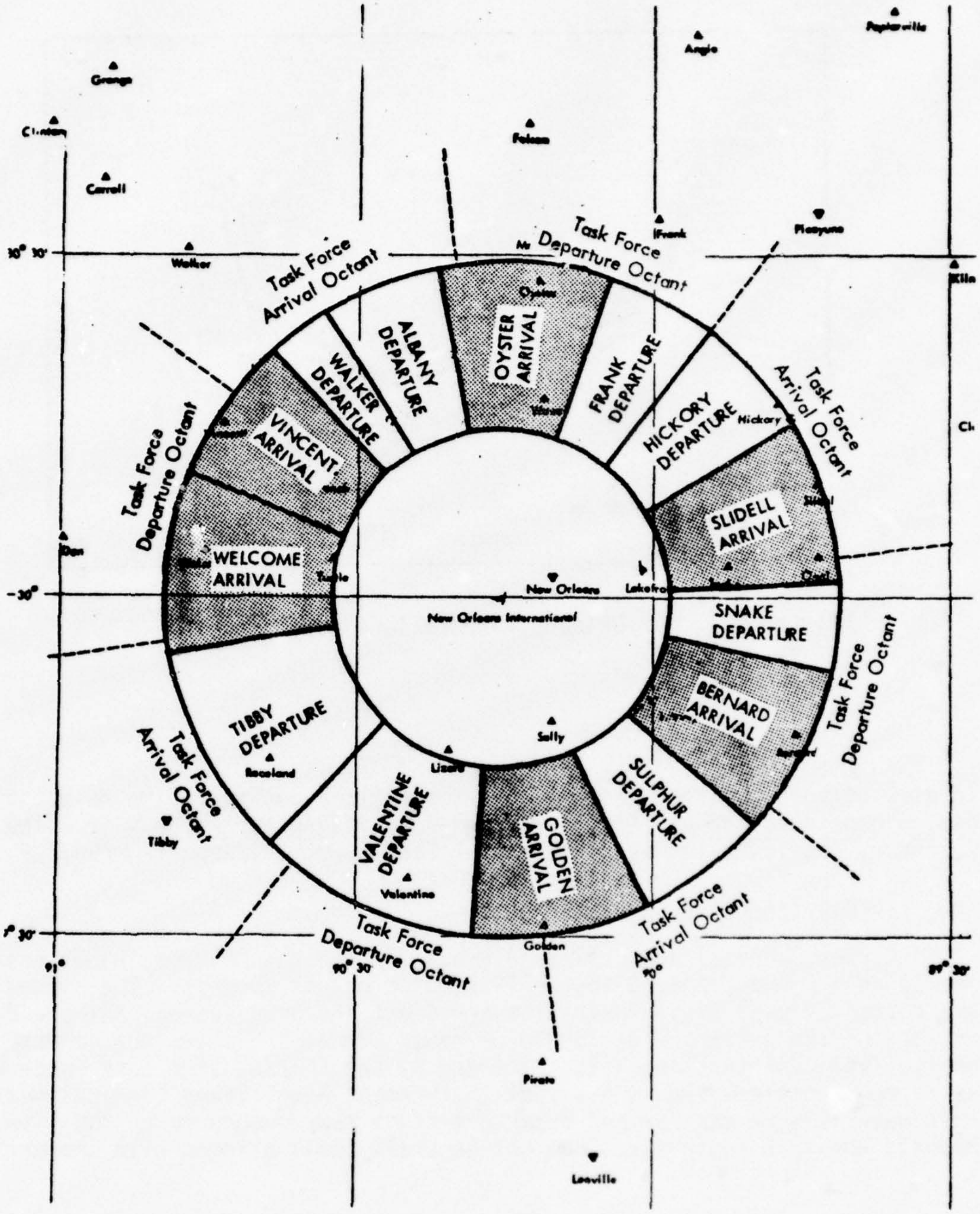


Figure 5.2 Current New Orleans Traffic Flow vs. the Task Force Octant Concept

and departure areas presented by the Task Force. The resolution of these conflicting airspace utilization concepts will be discussed further in the descriptions of the 1977 and 1982 terminal area designs.

Traffic density over each of the current arrival and departure areas can be estimated from scheduled air carrier data for December 1972.

ARRIVALS

Fix	Number	% of Arrivals
Slidell	57	30
Welcome	39	21
Vincent	33	17
Oyster	30	16
Golden	17	9
Bernard	12	6
Valentine	2	1

DEPARTURES

Fix	Number	% of Departures
Hickory	54	29
Tibby	40	21
Walker	34	18
Albany	18	10
Sulphur	17	9
Snake	15	8
Frank	10	5
Valentine	1	--

The traffic density over these fixes can be seen in the high altitude and low altitude traffic distribution diagrams, Figures 5.3 and 5.4, which were constructed from peak day IFR records for 1971 for city pairs exchanging ten or more IFR flights per day. The traffic depicted on these diagrams accounts for about two thirds of the New Orleans terminal area IFR traffic. The remainder of the IFR traffic would come from cities which exchange less than 10 flights per day with the New Orleans TRACON.

Navigation Facilities

The New Orleans terminal area has several navigation facilities in the area which can support both RNAV and conventional flight operations. The major facility in the area is the New Orleans VORTAC (MSY) which is located about 5 nm northeast of New Orleans International Airport. Other facilities which are used to provide routes and define intersections in the New Orleans Terminal Area are:

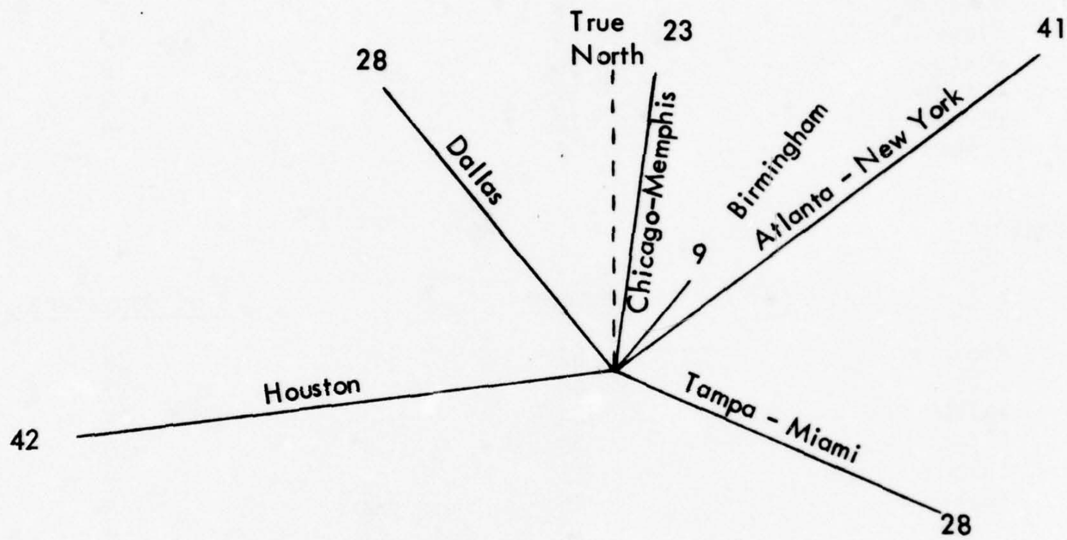


Figure 5.3 New Orleans High Altitude Traffic Distribution Diagram

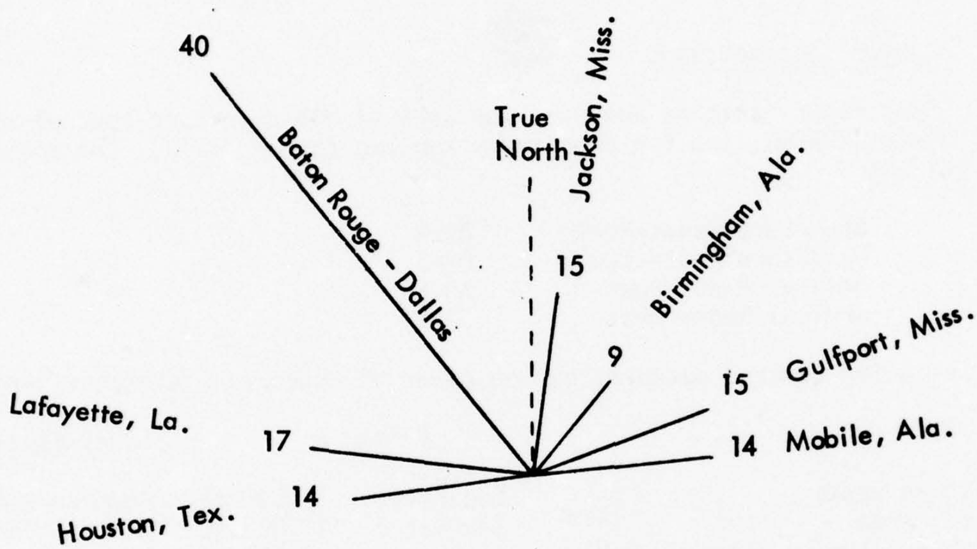


Figure 5.4 New Orleans Low Altitude Traffic Distribution Diagram

Name	ID	Type of Facility	Location from MSY VORTAC	
HARVEY	HRV	VORTAC	14 nm	Southeast
LEEVILLE	LEV	VORTAC	52 nm	South
GULFPORT	GPT	VORTAC	61 nm	East-Northeast
PICAYUNE	PCU	VORTAC	39 nm	Northeast
BATON ROUGE	BTR	VORTAC	64 nm	Northwest
TIBBY	TBD	VORTAC	41 nm	Southwest

Control Jurisdiction

Four radar position are used for arrival and departure control at the New Orleans TRACON, two for departures and two for arrivals. The positions are called:

Departure Radar-North	DR-N
Departure Radar-South	DR-S
Arrival Radar-East	AR-E
Arrival Radar-West	AR-W

The following general patterns can be observed concerning airspace jurisdiction:

Area	Altitude	Jurisdiction
Departure Gates	Sea Level - 11,000 ft	Departure Control
Descent Area	Sea Level - 11,000 ft	Arrival Control
TRACON (excluding descent area)	Sea Level - 5,000 ft	Departure Control
TRACON (excluding departure gates)	6,000 - 11,000 ft	Arrival Control

The departure gates are those areas designated as departure areas in Figure 5.2. The descent area is a 60°-90° sector which extends to the 30 nm circle of the Airport Surveillance Radar and which is centered on the extension of the active landing runway centerline. For example, when Runway 10 is being used for arrivals, the sector west of MSY including Vincent and Welcome Arrival Areas is used as the descent area. When Runway 28 is used for arrivals, the Snake Departure Area becomes part of the descent area and no departures are permitted through Snake except those coordinated with arrival control. Similarly, when Runway 01 is used for arrivals, Valentine Departure Area becomes part of the descent area for arriving aircraft.

The exact areas of jurisdiction change with the runways in use. The following chart shows a brief summary of the control jurisdictions.

Airspace Area	Landing Runway 1	10	19	28
Oyster Arrival	AR-E,AR-W	AR-E, AR-W	AR-E, AR-W	AR-E
Frank Departure	DR-N	DR-N	DR-N	DR-N
Hickory Departure	DR-N	DR-N	DR-N	DR-N
Slidell Arrival	AR-E	AR-E	AR-E	AR-E
Snake Departure	DR-N	DR-S	DR-N	AR-E

Bernard Arrival	AR-E	AR-E	AR-E	AR-W
Sulphur Departure	DR-N	DR-S	DR-N	DR-S
Golden Arrival	AR-E	AR-E	AR-E	AR-W
Valentine Departure	AR-W	DR-S	DR-S	DR-S
Tibby Departure	DR-S	DR-S	DR-S	DR-S
Welcome Arrival	AR-W	AR-E	AR-W	AR-W
Vincent Arrival	AR-W	AR-W	AR-W	AR-W
Walker Departure	DR-S	DR-N	DR-S	DR-N
Albany Departure	DR-S	DR-N	DR-S	DR-N

Satellite traffic to and from New Orleans Lakefront and New Orleans Naval Air Station are handled by departure control. When Runway 28 at MSY is in use, the arriving traffic at MSY within a five mile radius of both of the satellite airports is restricted to be 3000 ft or above. This permits satellite departures to use the 2000 ft altitude level until they are clear of MSY arrivals. When other runways are in use, separation is maintained by the departure radar controller.

Noise Constraints at MSY

Three of the runway operations at MSY have been designed as "Noise Sensitive" by the MSY tower. These operations are:

Arrival	- Runway 28
Departure	- Runway 01
Departure	- Runway 10

Unless these runways are specifically requested by the pilot, ATC will not assign them unless meterological conditions require their use. These restrictions apply to all turbojet aircraft and aircraft weighing more than 12,500 lbs.

5.1.1.2 The 1972 New Orleans Terminal Area Design

The 1972 New Orleans terminal area design is based entirely upon the current air traffic flow patterns used by the New Orleans TRACON. These flow patterns are depicted for two runway configurations in Figures 5.5 and 5.6. No independent RNAV routes were established for two reasons; first, there is a wide discrepancy in the flow patterns for the present New Orleans TRACON and in the flow patterns recommended by the RNAV Task Force. Most attempts to create new RNAV routes in the New Orleans area which were in alignment with the Task Force recommendations would create a traffic flow which conflicted with exisitng traffic flow patterns. This situation can be seen by referring to Figure 5.2 in which the present arrival and departure fixes are shown inside the 30 nm ring. The second reason for not establishing any independent RNAV routes is that the current routes generally serve the traffic demand directions. This can be seen by comparing the demand in Figures 5.3 and 5.4 with the route structure shown in Figures 5.5 and 5.6. The only available airspace for independent RNAV routes is south of MSY but according to the traffic distribution diagrams little traffic is handled in this area and the development of an RNAV route in this area is not warranted on the basis of traffic demand.

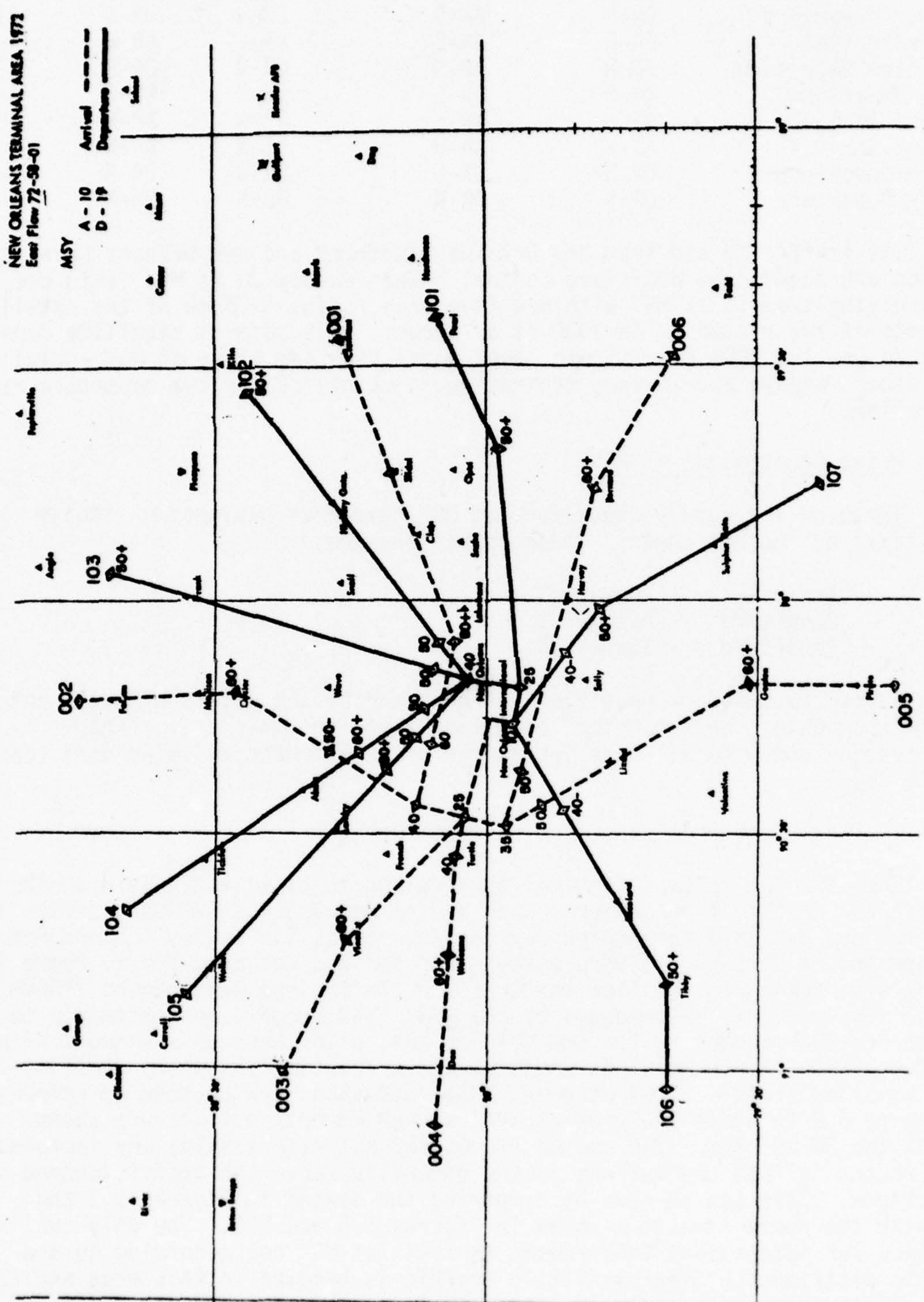


Figure 5.5 New Orleans Terminal Area – 1972 RNAV Routes, East Flow

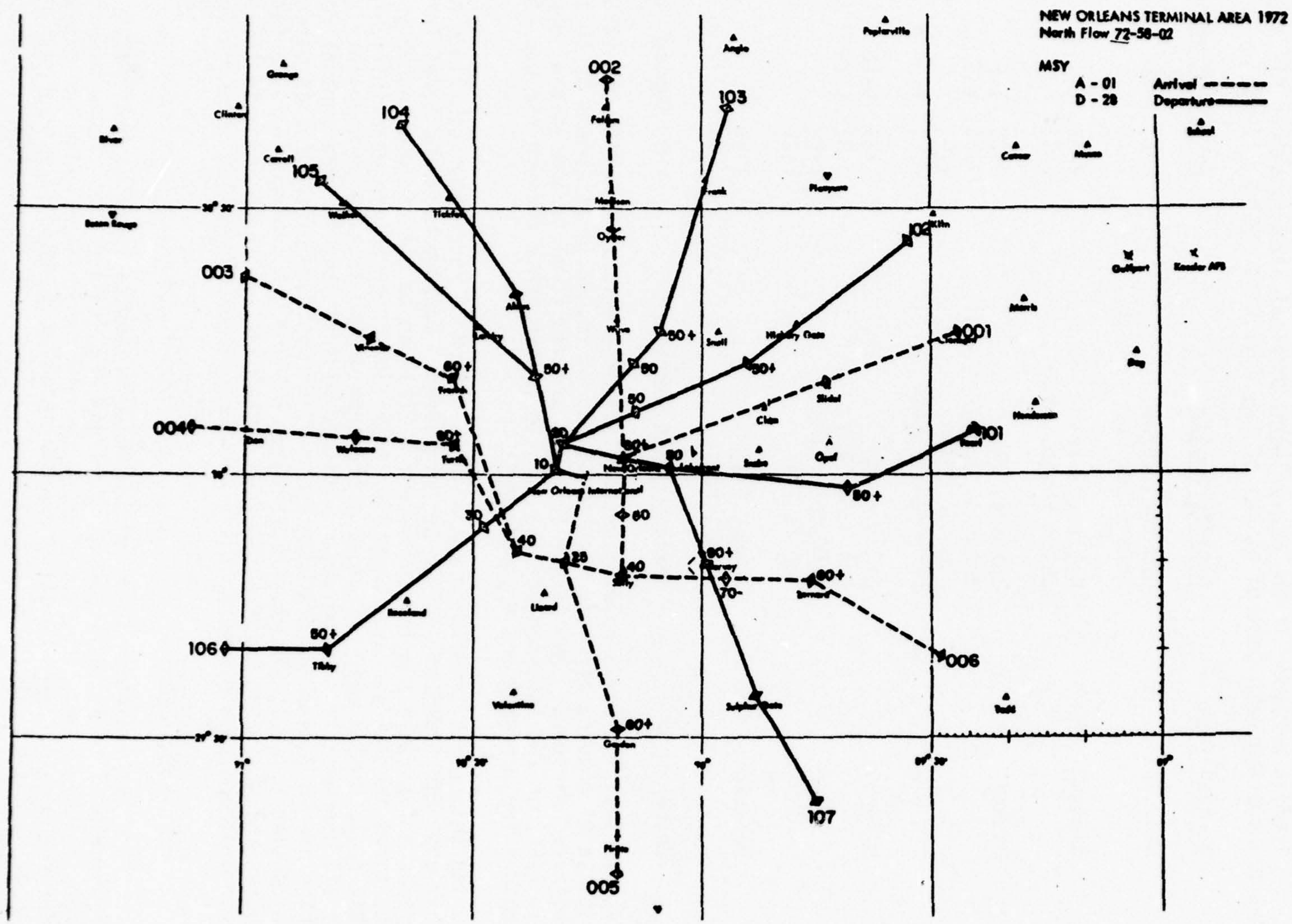


Figure 5.6 New Orleans Terminal Area - 1972 RNAV Routes, North Flow

Arriving Traffic

Traffic arriving at the New Orleans terminal area is handed off to the New Orleans Approach Control at one of the following arrival fixes:

Arrival Fix	Departure City	Arrival Route
Welcome	Houston, Texas	J-2, V-20
	Lafayette, La.	V-20
Vincent	Dallas, Texas	J-58, V-114
	Baton Rouge, La.	V-114
Oyster	Chicago, Ill.	J-35, V-9
	Memphis, Tenn.	J-35, V-9
	Jackson, Miss.	V-9
	Birmingham, Ala.	J-31, V-455W
Slidell	Atlanta, Ga.	J-37, V-20
	New York, N.Y.	J-37, V-20
	Gulfport, Miss.	V-20
	Mobile, Ala.	V-20
Bernard	Tampa, Fla.	J-58
	Miami, Fla.	J-58
Golden	Mexico, South America	V-9, Control 1447

Each arrival fix has a holding pattern airspace area associated with it which is capable of holding aircraft from 6,000 ft. to 14,000 ft at speeds up to 230 knots indicated airspeed. Navigation from the arrival fixes to the initial approach fix (IAF) or the intermediate fix (IF) is accomplished through the use of radar vectors for non-RNAV equipped aircraft.

During this first transition phase the location of radar approach fixes and RNAV approach fixes will often be coincident. Consequently the terms initial approach fix (IAF) and intermediate fix (IF) can be used interchangeably with the terms initial approach waypoint (IAWP) and intermediate waypoint (IWP). The RNAV route traces over essentially the same ground track with waypoints established at all appropriate turn points. Altitude restrictions for the arrival routes, which are in general accord with the current altitude procedures as discussed in Section 5.1.1.1, are shown in Figures 5.5 and 5.6. Aircraft following these routes and utilizing these altitude restrictions will have adequate IFR separation from departure traffic without any requirement for controller intervention.

Departing Traffic

Traffic departing from the New Orleans terminal area is restricted to 5000 ft. or below until they reach one of the eight departure areas. These departure areas begin at the 15 nm circle centered at the site of the ASR radar and extend outward from the terminal area to the 30 nm circle which is the lateral extent of the TRACON. In the vicinity of the airport aircraft are requested to maintain runway

heading until they reach a specified altitude and then they are given radar vectors to intercept their assigned departure route. These routes generally follow the patterns as shown in the departure routes of Figures 5.5 and 5.6. The departure routes make use of the following fixes:

Departure Fix	Arrival City	Departure Route
Walker	Dallas, Texas	V-114N, J-58
	Baton Rouge, La.	V-114N
Tickfaw	Chicago, Ill.	MSY-320°R, Tickfaw, MCB
(Albany Gate)	Memphis, Tenn.	MSY-320°R, Tickfaw, MCB
	Jackson, Miss.	MSY-320°R, Tickfaw, MCB
Frank	Chicago, Ill..	MSY-010°R, Frank, MCB
	Memphis, Tenn.	MSY-010°R, Frank, MCB
	Jackson, Miss.	MSY-010°R, Frank, MCB
	Birmingham, Ala.	MSY-010°R, Frank, HBG, V-455 or MSY-010°R, Frank, MEL, J-31
Hickory	Atlanta, Ga.	MSY-045°R, Hickory, MOB,J-37
	New York, N.Y.	MSY-045°R, Hickory, MOB,J-37
	Gulfport, Miss.	MSY-045°R, Hickory, GPT
	Mobile, Ala.	MSY-045°R, Hickory, GPT, V-20
Snake Gate	Tampa, Fla.	Radar Vecotrs to J-58
	Miami, Fla.	Radar Vectors to J-58
Sulphur Gate	Tampa, Fla.	MSY-145°R, J-86
	Miami, Fla.	MSY-145°R, J-86
Valentine	Mexico, South America	MSY-200°R, Control 1447
Tibby	Houston, Texas	V-20S, J-37
	Lafayette, La.	

5.1.1.3 The 1972 Task Force Concept at New Orleans

It is quite apparent that the traffic flow patterns in the terminal transition area at New Orleans do not follow the octant concept described by the Task Force Report [1]. There are seven departure areas and six arrival areas at New Orleans rather than the four arrival and four departure octants recommended by the Task Force. In comparing these current arrival and departure areas with the enroute traffic flow depicted on the traffic distribution diagrams it is apparent that the present terminal route structure at New Orleans provides routes to and from the high density traffic directions in a reasonably direct manner with no route length penalty. A few altitude restrictions are necessary in the vicinity of the airport in both flows in order to separate crossing arrival and departure traffic. Outside of a 20 nm radius from the airport no altitude restrictions are necessary for arrivals or departures.

Since the enroute traffic was served with reasonably direct routes to and from the terminal area and since very little airspace remained in the New Orleans area for independent routes, all of the 1972-1977 time period routes were designed to overlie the present radar vector and VOR routes. No difficulty was encountered in developing these overlying RNAV routes. From a route design standpoint, it is possible to develop a compatible set of RNAV and radar vector/VOR routes in both of the runway configurations at New Orleans for which designs were constructed.

5.1.1.4 The Amended 1972 New Orleans Terminal Area Design

The most significant change required to the 1972 New Orleans route structure was the addition of several departure routes. These departure routes go to high and low altitude VORTACs that are not shown on the New Orleans area map. Specifically, two more departure routes were added to the northeast and two were added to the southwest. The route departing nearly south of the New Orleans, depicted as route 107 on Figures 5.7 and 5.8 goes out to a low frequency airway and serves Mexican traffic.

Two arrival routes were also added to the amended 1972 design. The first route is depicted as route 002 in Figures 5.7 and 5.8, and arrives from the northeast to Madison Intersection. The second arrival, depicted as route 003, also arrives from the northeast. It generally parallels route 004, but it is a high altitude route from the Mobile VORTAC. In the east flow configuration (Figure 5.7) the initial approach segments were changed to provide a downwind, base and final type approach path. In the original design the north and south arriving traffic proceeded directly from the initial approach fix to the base leg. In the north flow configuration it was determined that arrivals from the southeast proceed over Sulphur Gate to a base leg entry near Sally Intersection rather than the arrival over Bernard Intersection as had been depicted in the previous design. Southbound departures generally go out near Valentine Intersection rather than over Sulphur Gate as had been depicted in the previous design.

5.1.2 Denver

5.1.2.1 Characteristics of the Denver Terminal Area

Traffic flow in the Denver Terminal Area is dominated by Stapleton International Aiport (DEN). The one other airport in the Denver Area that handles any sizeable IFR traffic flow is Buckley ANGB (BKF). From the data on the 1969 peak day tape, the traffic activity at these two airports was:

Airport	IFR Operations	Percent Low Altitude
Denver	662	30%
Buckley	54	22%

The other airports in the Denver area handled by the Denver Approach Control are Arapahoe County, Jeffco, and Sky Ranch. Due to the dominance of Stapleton, the design considered only traffic flow into and out of this airport.

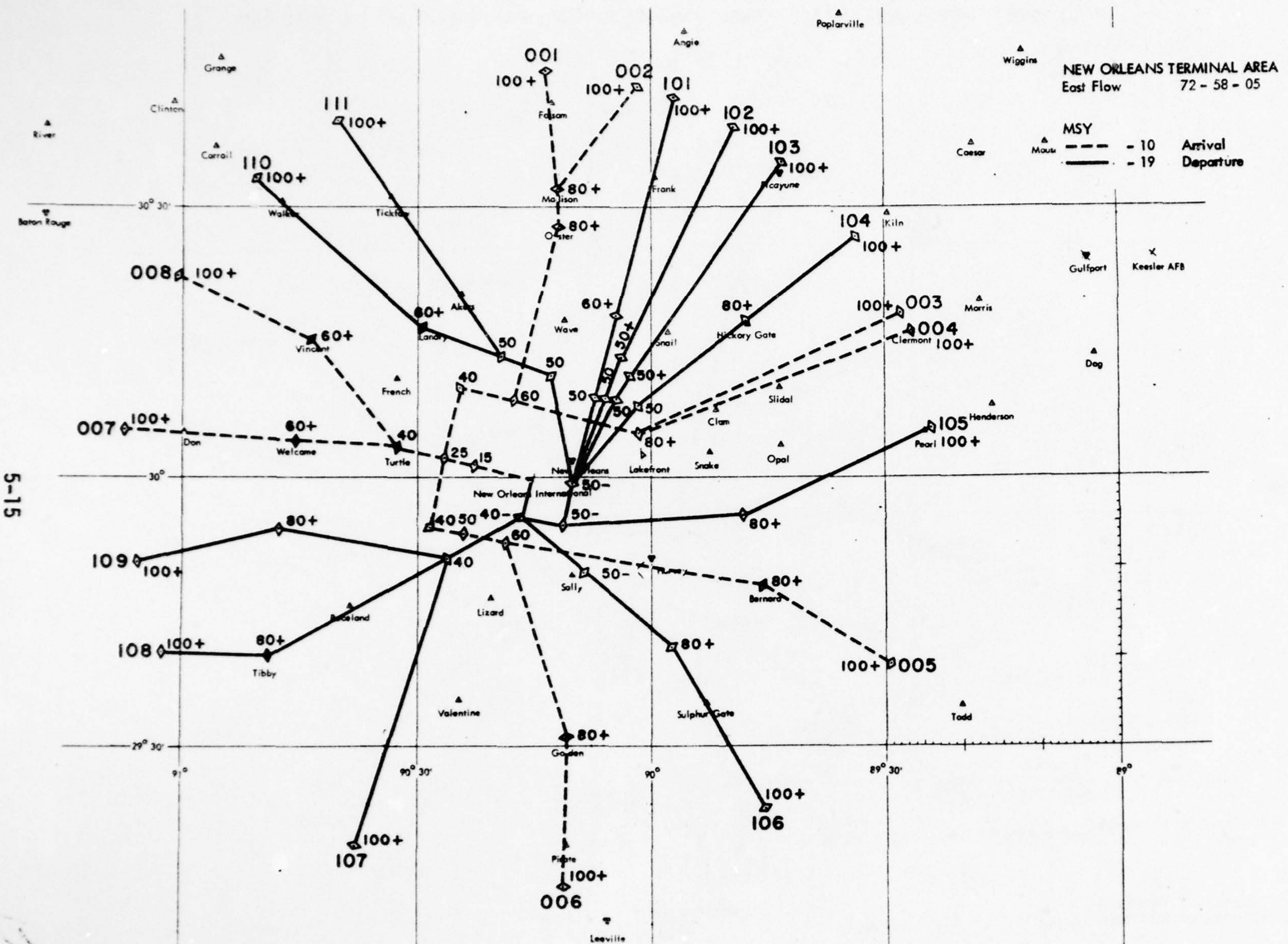


Figure 5.7 Amended New Orleans Terminal Area – 1972 RNAV Routes, East Flow

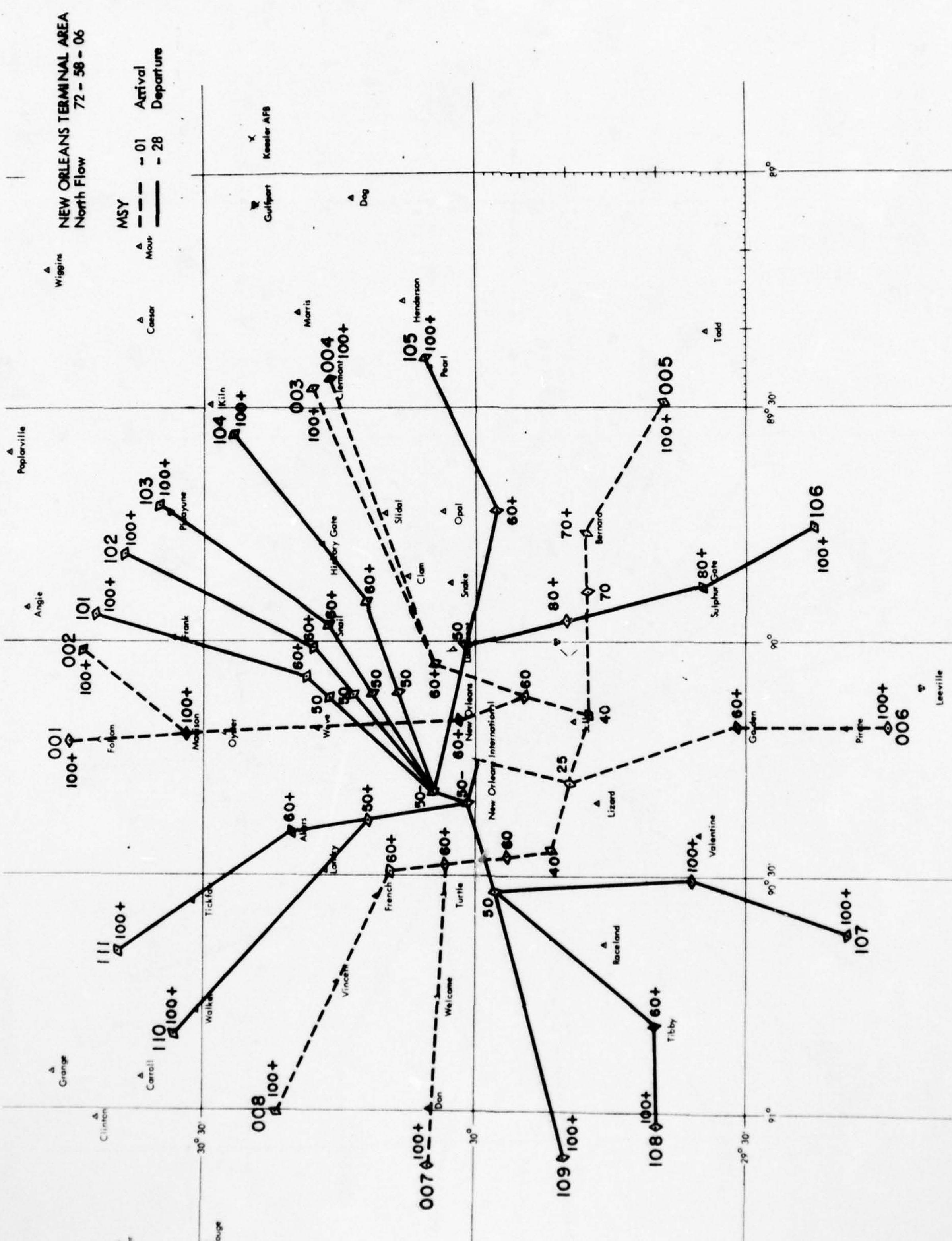


Figure 5.8 Amended New Orleans Terminal Area - 1972 RNAV Routes, North Flow

Runway Orientation and Utilization

The physical characteristics of the Denver runways are shown in Figure 5.9. Runways 8L-26R and 8R-26L are not separated sufficiently to permit independent IFR operations. However, the location of 8R-26L and 17-35 permit ILS arrivals on runway 26L and departures on 35 on a non-interfering basis. This is generally the preferred configuration. One complicating factor, however, is the fact that aircraft over 285,000 lbs are not permitted on runway 17-35 due to the presence of a highway overpass that is not stressed for weights in excess of those stated. Consequently, heavy aircraft must depart on 8R-26L. This problem is handled on an individual basis by the controller and was not given special consideration in the Denver design.

Operationally, the most difficult runway configuration is the east flow with arrivals and departures using 8R. The high terrain to the west of Denver leaves the arrival controller with very little airspace with which to descend and slow down the arrivals. Consequently, departures are often routed up to 20 miles north of the airport in order to keep the airspace free for the eastbound arrivals. This, of course, increases the travel distance for westbound departures. The other two configurations that are used at Denver are the north flow (Runway 35) and south flow (Runway 17) with aircraft over 285,000 lbs using 8R or 26L for the reasons mentioned earlier and small aircraft using 8L or 26R.

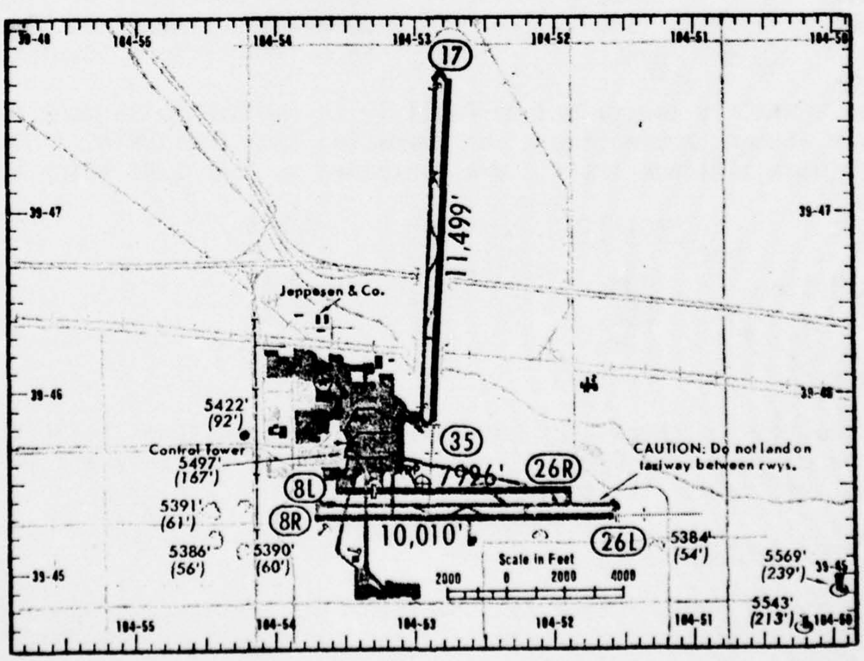


Figure 5.9 Denver Airport Configuration

These two flows have relatively straightforward traffic patterns.

The two flows that were selected for detailed analysis were the preferred west flow configuration and the operationally difficult east flow.

Terminal area traffic flow for the present Denver terminal area is shown in Figure 5.10 with the Task Force octant overlaid. The feeder fixes for DEN are:

Feeder Fix	Percent of Arrivals
Byers (East)	34%
Platte (North) Longmont (North) Lyons (Northwest)	28%
Shawnee (Southwest)	17%
Elizabeth (South)	21%

These fixes are formed by three VORTAC navigation facilities in the Denver area. These are:

VORTAC	IDENTIFIER	LOCATION
Denver	DEN	10 miles northeast of Stapleton
Kiowa	IOC	30 miles southeast of Stapleton
Gill	GLL	48 miles north of Stapleton

The Denver VORTAC is the principal facility in the area with most routes to and from Denver either terminating at or emanating from the VORTAC. Departure routes for high altitude traffic are contained on four SIDs which are:

SID	FACILITY	RADIAL
North Platte - 2	DEN	054°
Superior - 4	DEN	264°
Golden - 4	DEN	244°
Pueblo - 2	DEN	146°

In addition to these SIDs the low altitude departures leave the Denver area to the north on the DEN 001° radial (Victor 4N-89E-207) and to the southwest on the DEN 194° radial (Victor 89).

Control Jurisdiction

The control jurisdiction at Denver for the IFR traffic operations at Stapleton are divided among two arrival and two departure controllers (AR-1, AR-2, DR-1 and DR-2). Their areas of responsibility change as the runway configurations change. This is due in part at least to the higher workload involved in handling the eastbound arrivals coming over the mountains in the east flow configuration.

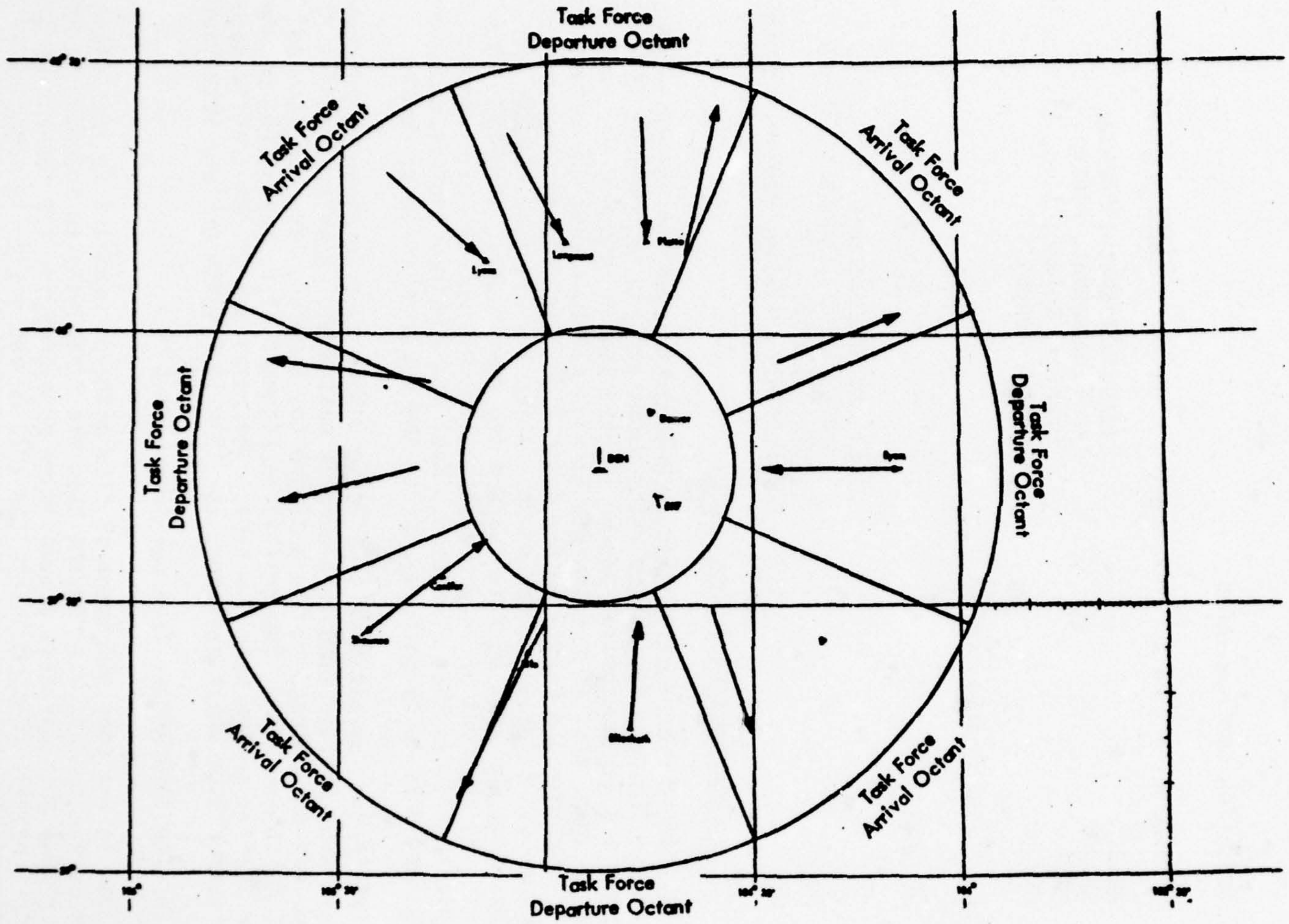


Figure 5.10 Current Denver Traffic Flow vs. the Task Force Octant Concept

The control jurisdiction for the two flows that were used in the terminal design are:

West Flow Configuration

Controller	Fixes
AR-1	Byers, Elizabeth, Shawnee
AR-2	Lyons, Longmont, Platte
DR-1	Superior, Golden, Silo, Elizabeth
DR-2	Hudson, Roggen

East Flow Configuration

Controller	Fixes
AR-1	Elizabeth, Shawnee
AR-2	Byers, Lyons, Longmont, Platte
DR-1	Silo, Pueblo
DR-2	Superior, Golden, Hudson, Roggen

Enroute Connecting Points

A traffic distribution diagram was constructed for Denver based upon peak day enroute IFR data for cities which exchanged ten or more IFR flights per day. The traffic distribution for Denver is depicted in Figure 5.11. As can be seen in the diagram, most of the traffic is high altitude with the exception of Colorado Springs and Pueblo to the south (105 flights) and Cheyenne (15 flights) and Casper (15 flights) to the north. A few low altitude flights arrive from and depart to the east (6 flights) and the southeast (6 flights). The high mountains to the West of Denver essentially preclude the existence of low altitude traffic in that direction. Most low altitude traffic desiring to go to the West does so by going either to the south or north of Denver.

While the low altitude traffic at Denver is predominantly north-south, the high altitude traffic flow is generally east-west. Heaviest traffic flows occur to New York and Chicago to the east and Los Angeles, San Francisco and Salt Lake City to the west. The traffic in Figure 5.11 represent 66% of the total Denver traffic on the peak day tape. The remainder of the traffic departs to or comes from cities which exchange less than 10 flights per day with Denver.

5.1.2.2 The 1972 Denver Terminal Area Design

Due to the poor alignment of flow patterns relative to the octant concept in the Denver area it was thought that the first step in introducing RNAV into the terminal area was best accomplished by overlaying the conventional routes with RNAV routes. Consequently, the 1972 Denver design is composed of only the current radar vector routes over which the RNAV routes are constructed. The present Denver terminal route structure is shown in Figures 5.12 and 5.13 for the Arrival -26, Departure -35 and Arrival -8, Departure -8 configurations respectively.

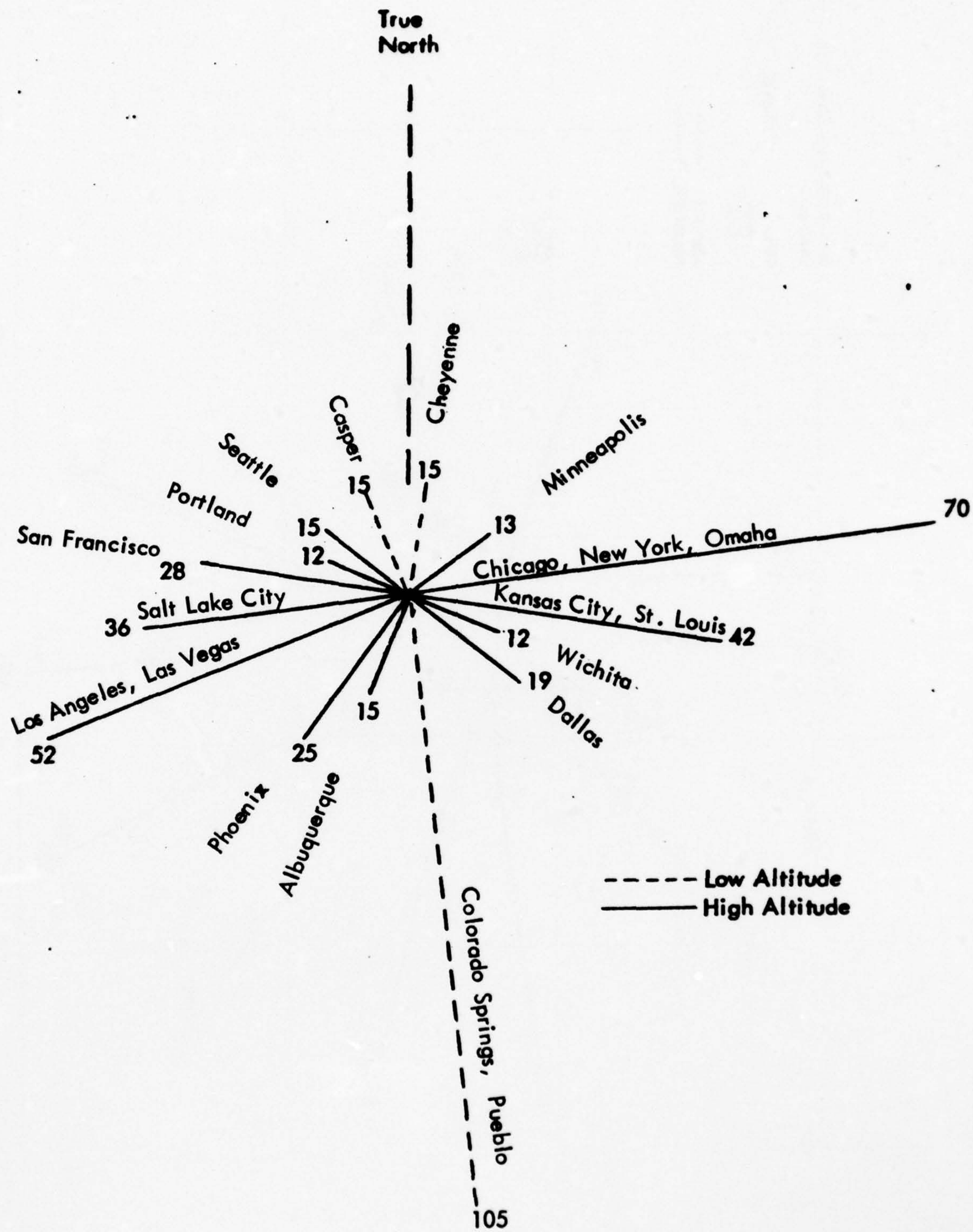


Figure 5.11 Denver Low and High Altitude Traffic Distribution Diagram

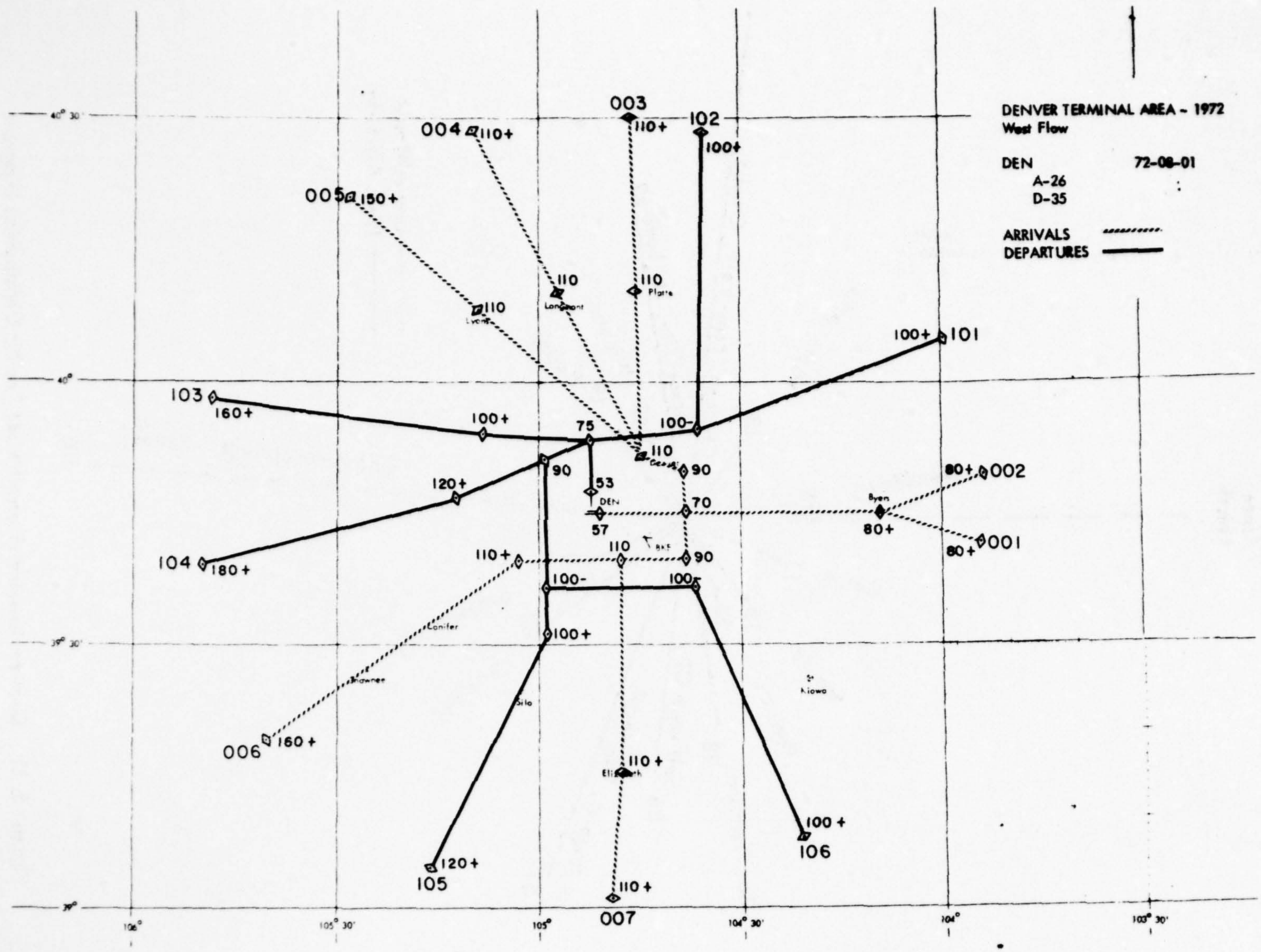


Figure 5.12 Denver Terminal Area - 1972 RNAV Routes, West Flow

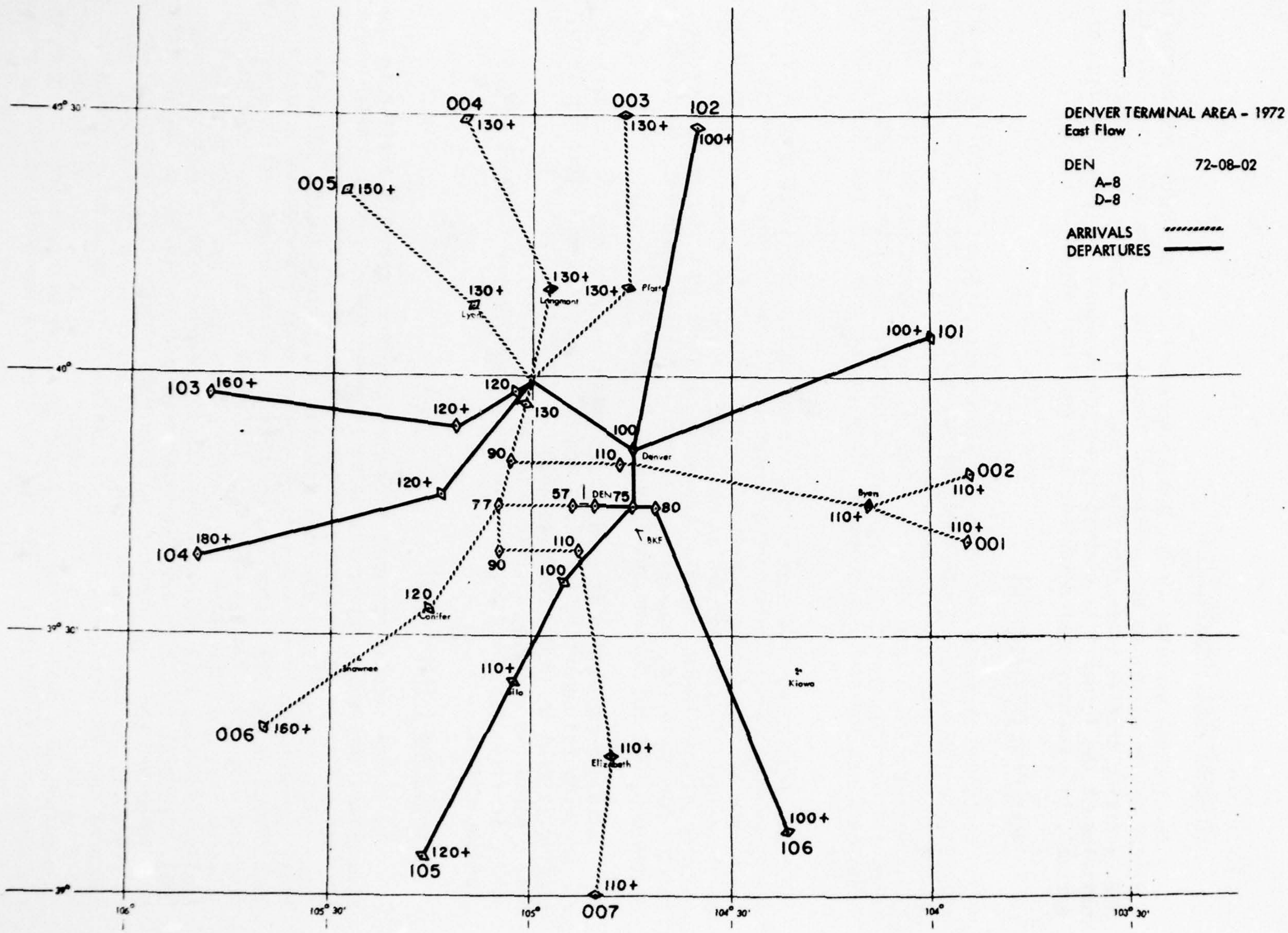


Figure 5.13 Denver Terminal Area - 1972 RNAV Routes, East Flow

Terminal Area Traffic Flow

The traffic arriving in the Denver terminal area generally proceeds along a Victor or Jet Airway to the arrival or feeder fix for the direction of arrival. Most arriving traffic comes into the feeder fix on a Denver VORTAC radial. After arriving at the feeder fix, traffic is vectored, depending upon direction of arrival, to a conventional downwind, base and final approach leg.

West Flow (Figure 5.12)

Westbound arrivals intercept the ILS course at Byers and follow the ILS directly to the runway. Southbound and southeastbound traffic proceeds directly to the Denver VORTAC and from there proceeds from the VORTAC on a 110° heading to intercept a right base leg 5 nm north of the intermediate fix (IF). Northeastbound and northbound arrivals intercept a conventional downwind leg 5 nm south from the final approach leg whereupon they intercept a left base leg 5 nm south of the IF.

All departures climb out on the runway heading until reaching 7500 feet whereupon they turn to intercept a Denver VORTAC radial on their appropriate SID. All of the airport departure patterns are relatively standard with the exception of route 106. This route circles about 210° around the airport before intercepting the 146° Denver radial. Obviously, a right turn out would have been shorter for route 106, however such a traffic pattern would interfere with arrival routes 003, 004 and 005 and possibly some Buckley traffic.

Altitude separation is used at Denver in order to provide independent paths for arriving and departing traffic. Generally on crossing routes the departing traffic is held to 10,000 feet (about 5,000 feet above ground level) until they have cleared the arriving traffic which is at 11,000 feet or above. In other words, arrivals top the departures in the present Denver terminal area on crossing routes.

East Flow (Figure 5.13)

As in the case of the west flow configuration, arriving traffic in the east flow enters the Denver terminal area on a Denver VORTAC radial. After crossing the feeder fix for the designated arrival route, the traffic proceeds via radar vectors in a conventional downwind and base leg pattern to the IWP whereupon the final approach leg is intercepted. Eastbound traffic arrives on a base leg or goes direct to the IWP (depending on traffic) and westbound traffic uses a downwind and base leg. The arrivals from the north (Lyons, Longmont and Platte) converge into one flow about 15 nm north of the IWP. The major problem for controllers in using this flow concerns the eastbound arrivals (routes 005 and 006). These aircraft are arriving over high terrain (14,000 to 16,000 feet) at high speed and they must descend and slow down almost simultaneously so as not to overshoot the airport. Additionally, should there be considerable traffic in the area such that some maneuvering is necessary for sequencing, the controller has very little airspace in which to vector the aircraft due to the high terrain. As a consequence, most of the west bound departure aircraft are routed north of the airport 15 to 20 nm in order to clear the area for arrivals. This procedure

adds both time and distance to the west departures (routes 103 and 104). The remaining departure routes are conventional in nature in that the aircraft climb to 7500 feet and then turn to intercept their appropriate departure radial. Again, in this flow the arrivals top the departures.

Enroute Connecting Points - Both Flows

In this section the routes depicted in Figures 5.12 and 5.13 are described in terms of the appropriate SID or STAR and the navigation facility which they use.

Arrivals

001 Mustang Two Arrival - Lamar VORTAC
Lamar 320° radial to intercept Denver 090° radial to Byers Intersection at Runway 26L localizer.

002 Akron One Arrival - Akron VORTAC
Akron 229° radial to intercept Runway 26L localizer at Byers Intersection (Also Victor 8S).

003 Victor 19-89 - Cheyenne VORTAC,
Cheyenne 166° radial, Denver 346° radial to Platte Intersection.

004 Antelope Two Arrival - Rock Springs VORTAC,
Rock Springs 091° radial, Gill 277° radial, to intercept the 321° radial to Longmont.

005 Elk One Arrival - Rock Springs VORTAC,
Rock Springs 091° radial to intercept the Denver 300° radial to Lyons.

006 Timberline Two Arrival - Grand Junction VORTAC,
Grand Junction 068° radial to intercept the Denver 219° radial to Shawnee or Conifer Intersection.

007 Peublo Tower Enroute Arrivals - Denver 170° radial to Elizabeth Intersection.

Departures

101 North Platte Departure - Intercept the Denver 054° radial to the 239° radial to North Platte VORTAC (Victor 172).

102 Intercept the Denver 001° radial to the Gill 180° radial to Gill VORTAC (Victor 207-4N-89E).

103 Superior Three Departure - Intercept the Denver 264° radial to the 082° radial of Kremmling VORTAC (Victor 8-200, near Jet 56, 116).

104 Golden Three Departure - Intercept the Denver 244° radial to the Grand Junction 059° radial to Grand Junction VORTAC (Jet 60-80).

Departures (Continued)

105 Victor 89 - Intercept the Denver 194° radial to intercept the Gunnison 050° radial (Near Jet 13).

106 Denver - Pueblo Two Departure - Intercept the Denver 146° radial to the Peublo 351° radial to Peublo VORTAC (Victor 19).

5.1.2.3 The 1972 Task Force Concept at Denver

The terminal area traffic flow at Denver is not in general agreement with the octant concept in the terminal transition area. Many of the departure gates and feeder fixes in the eastern part of the terminal area are in direct opposition to the octant flow. Most notable are the Byers arrivals for routes 001 and 002 and the Roggen departures for route 101. In the west the traffic flow does correspond more to the octant concept with Lyons and Shawnee arrivals located in octant arrival areas (routes 005 and 006 respectively). The departure routes 103 and 104 are also located in an octant departure area. Routes to the north and south are generally not well aligned with the octant concept.

The traffic flow in the terminal maneuvering area is generally patterned in a manner that is consistent with the Task Force concept. Some allowances are necessary to accommodate the perpendicular runway operation for the west flow (Figure 5.12). This does cause route 106 to be routed in a circuitous manner in order to avoid conflicts with the traffic on final approach to runway 26. Route 106 also has a fairly severe altitude restriction until arrival route 007 over Elizabeth is cleared.

In the east flow (Figure 5.13) departures to the west on routes 103 and 104 are routed well north of the airport in order to achieve sufficient altitude to clear the mountainous terrain to the west. These routes are costly to the user in terms of both fuel and time penalties.

Since several radar vector/VOR arrival and departure routes were available to the Denver airspace user in near optimum locations and because of the difficulty in laying independent RNAV routes at Denver without creating conflicts with current terminal area traffic patterns, no independent RNAV routes were developed for the 1972-77 time period designs.

No difficulty was encountered in overlying the RNAV routes on the radar vector/VOR routes with the possible exception of departure route 105 in the east flow (Figure 5.13). Departures on this route must execute a sharp right turn of about 135° in order to proceed on course after leaving the runway heading. It may be operationally desirable to locate another waypoint on this route near the departure waypoint in order to reduce the turns to less than or equal to 90°.

5.1.2.4 The Amended 1972 Denver Terminal Area Design

The Denver terminal area was not visited due to schedule incompatibilities between the briefing team and the Rocky Mountain Region controllers. However, a preliminary version of this report was provided for review by the Rocky Mountain personnel. Written comments on the time phased designs and the modified design

guidelines were then obtained from the Region. Changes were made to the 1972 Denver route design based upon these written comments plus corresponding inputs from similar problems in other terminal areas. All of the following changes apply to both the east and west flow configurations.

The most significant change that was made to the Denver design is the addition of arrival and departure routes. These routes are based upon high and low altitude routes entering and leaving the Denver area. The amended 1972 Denver terminal designs are shown in Figures 5.14 and 5.15. Departure routes 102, 107 and 109 were added. Also, arrival route 002, 004 and 005 were included in the amended design but were not shown in the original design (Figures 5.12 and 5.13). These routes were added as a result of revised information concerning Denver arrivals and departures that use VOR facilities that were not considered in the initial design task.

5.1.3 Philadelphia

5.1.3.1 Characteristics of the Philadelphia Terminal Area

Airport Configuration

The Philadelphia Terminal Area is made up of one primary airport, Philadelphia International (PHL), and several satellite airports with varying amounts of instrument operations. The instrument traffic for PHL and the major satellites is summarized in Table 5.1. This data is taken from the IFR peak day on which the airport is identified as the origin or destination airport.

TABLE 5.1 DAILY INSTRUMENT IFR OPERATIONS (1971 Peak Day Tape)

Airports	Daily Operations	% Low Altitude Flights
Philadelphia International (PHL)	618	48%
North Philadelphia (PNE)	25	88%
Mercer County, Trenton, N.J. (TTN)	22	77%
Greater Wilmington, Del. (ILG)	83	76%

During the period (1971) the IFR runway at Willow Grove Naval Air Station was closed for repairs. Consequently, any IFR traffic at this facility is not reflected in the traffic activity statistics.

As a result of the relatively low traffic activity at the satellite airports, it was evident that the designs should be based primarily upon the airport configuration at PHL with consideration given to the satellite traffic flows after the PHL traffic is accommodated.

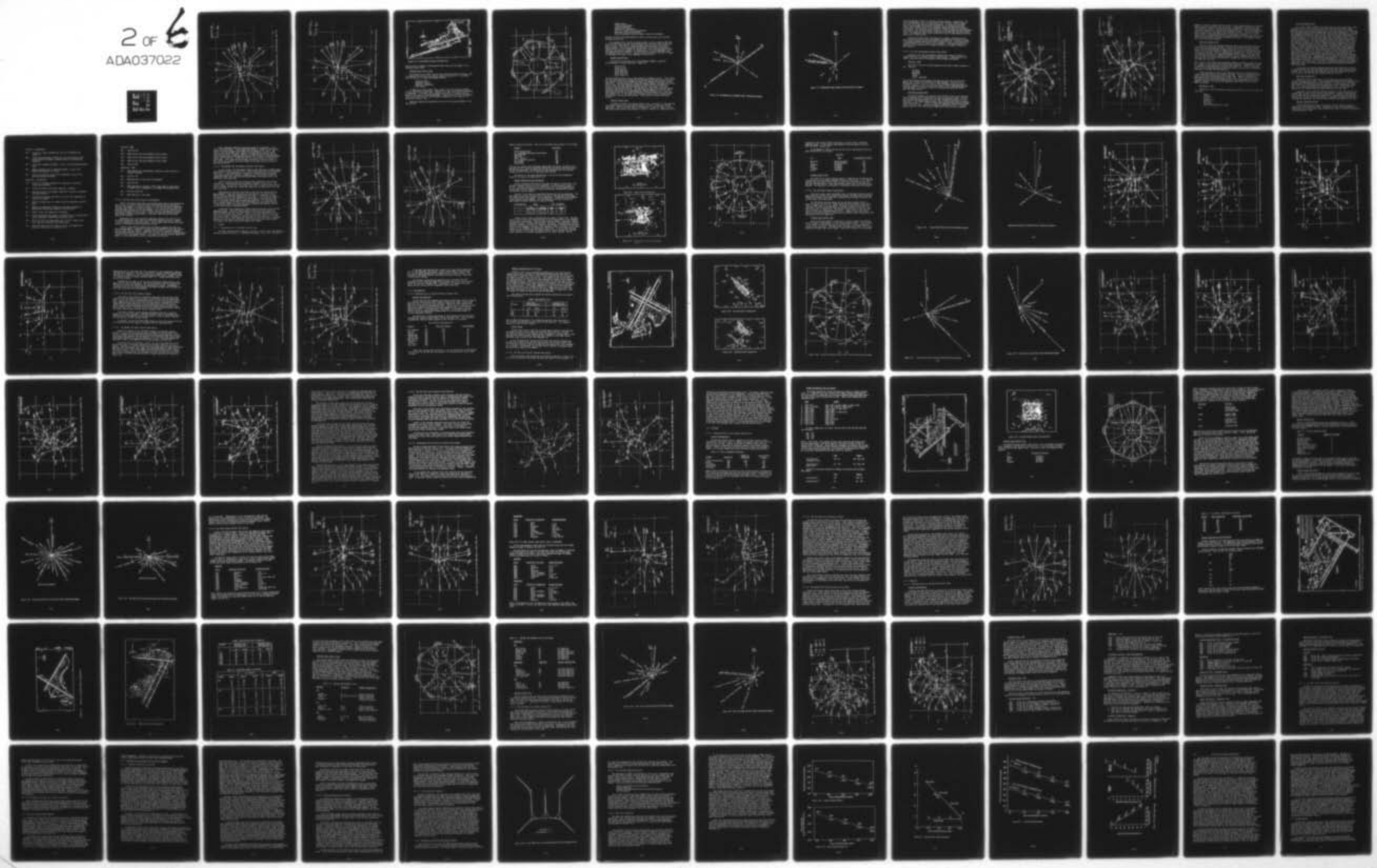
Runway Orientation and Utilization

The primary runways at PHL are the 9R-27L and 9L-27R combinations (Figure 5.16). Runway 9R has Category II ILS and was considered to be the primary IFR landing runway, however, traffic is about evenly divided between the 9/27 operation. Consequently, the two traffic flows selected for detailed

AD-A037 022 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
TERMINAL AREA DESIGN - ANALYSIS AND VALIDATION OF RNAV TASK FOR--ETC(U)
OCT 75 E D MCCONKEY , W H CLARK DOT-FA72WA-3098

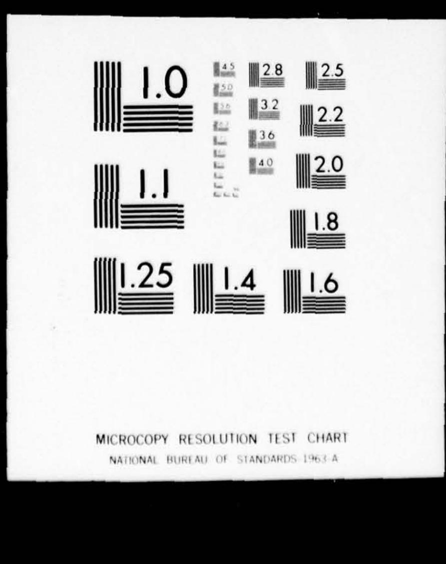
UNCLASSIFIED FAA-RD-76-194 NL

2 OF 6
ADA037022



2 OF 6

ADA037022



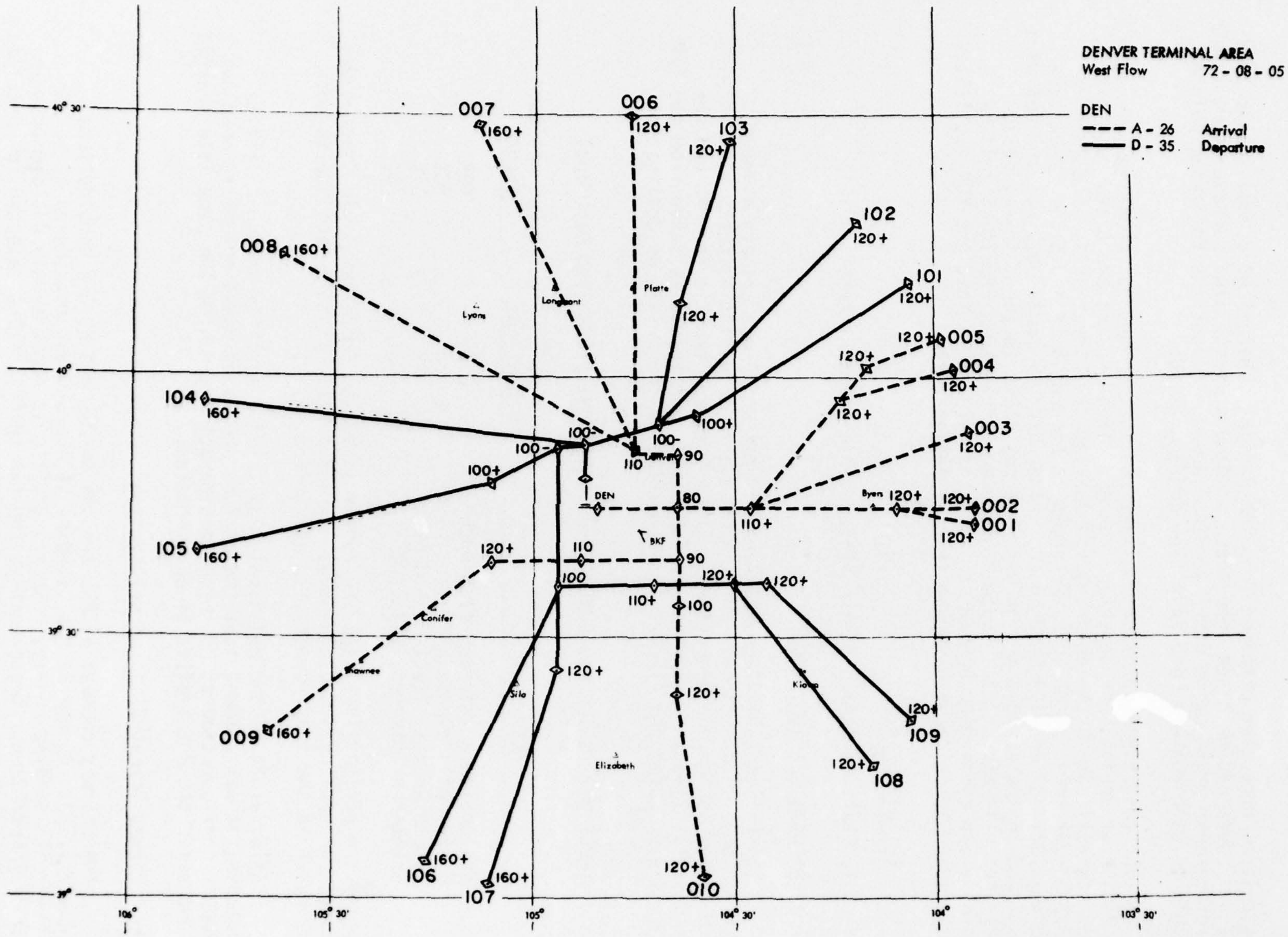


Figure 5.14 Amended Denver Terminal Area - 1972 RNAV Routes, West Flow

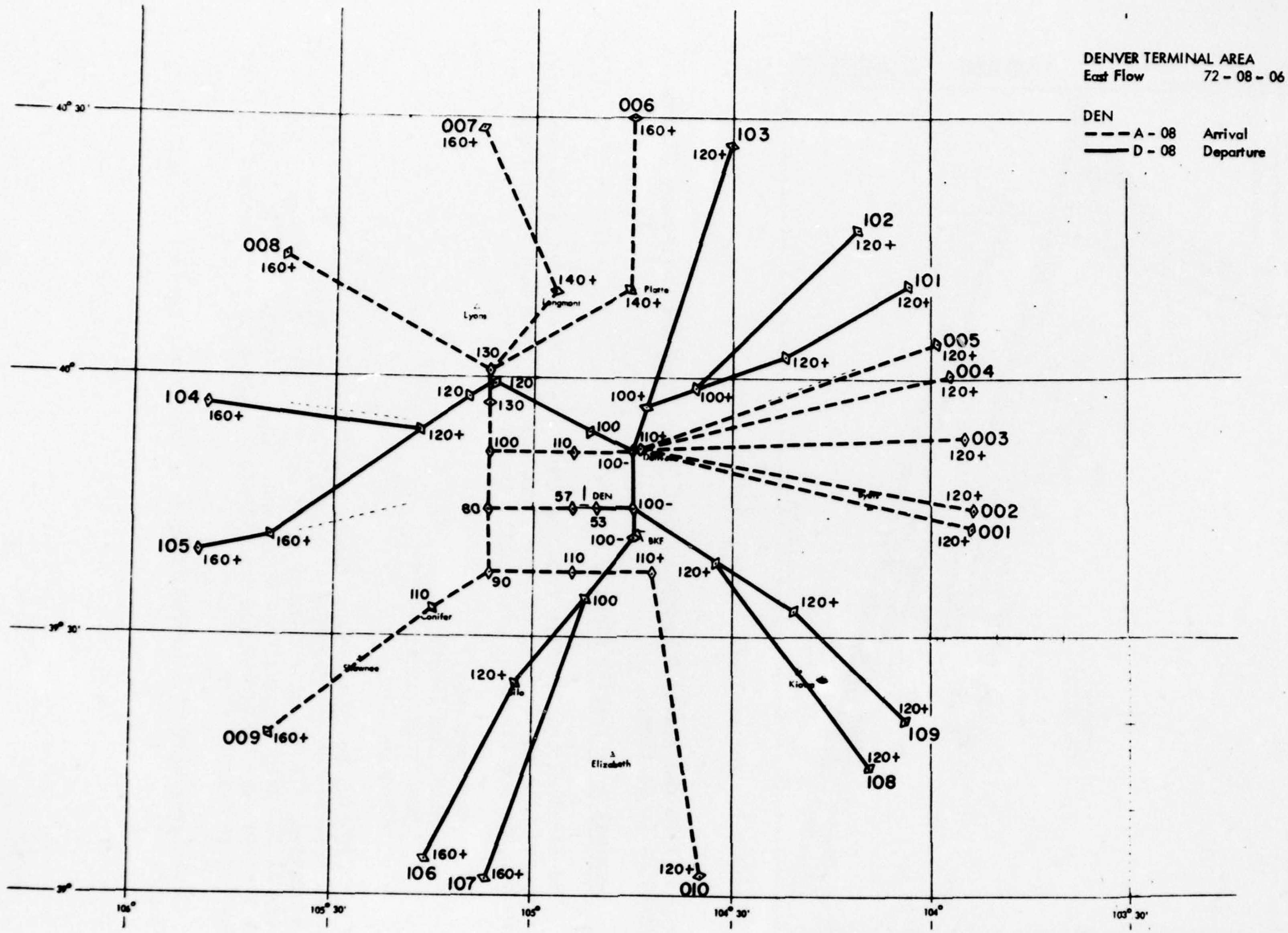


Figure 5.15 Amended Denver Terminal Area - 1972 RNAV Routes, East Flow

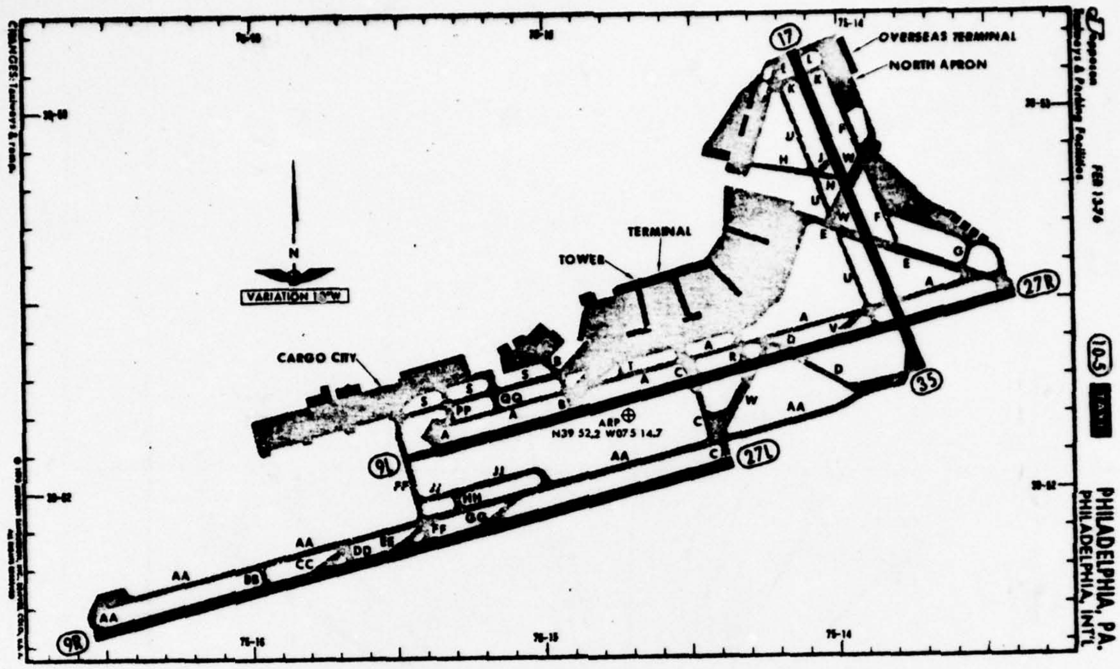


Figure 5.16 Philadelphia Airport Configuration

analysis were the Runway 9 configuration (east flow) and the Runway 27 configuration (west flow).

Terminal Area Traffic Flows

The terminal area traffic flow for the present Philadelphia terminal area is compared with the Task Force octant concept in Figure 5.17. The feeder fixes for PHL are (in order ofestimated traffic):

Bucktown (West)
Woodstown (South)
Newcastle (Southwest)
urner (North)

In addition to these feeder fixes, traffic arriving from the northeast such as from Boston and New York - Kennedy flies over Coyle VORTAC and proceeds to Woodstown. If the west flow is being used, traffic is vectored to the Runway 27 ILS prior to reaching Woodstown. Tower enroute traffic from Atlantic City arrives over Millville and proceeds to Woodstown or the Runway 27 ILS depending on traffic flow.

Departures generally proceed direct to one of the several VORTACs in the area such as:

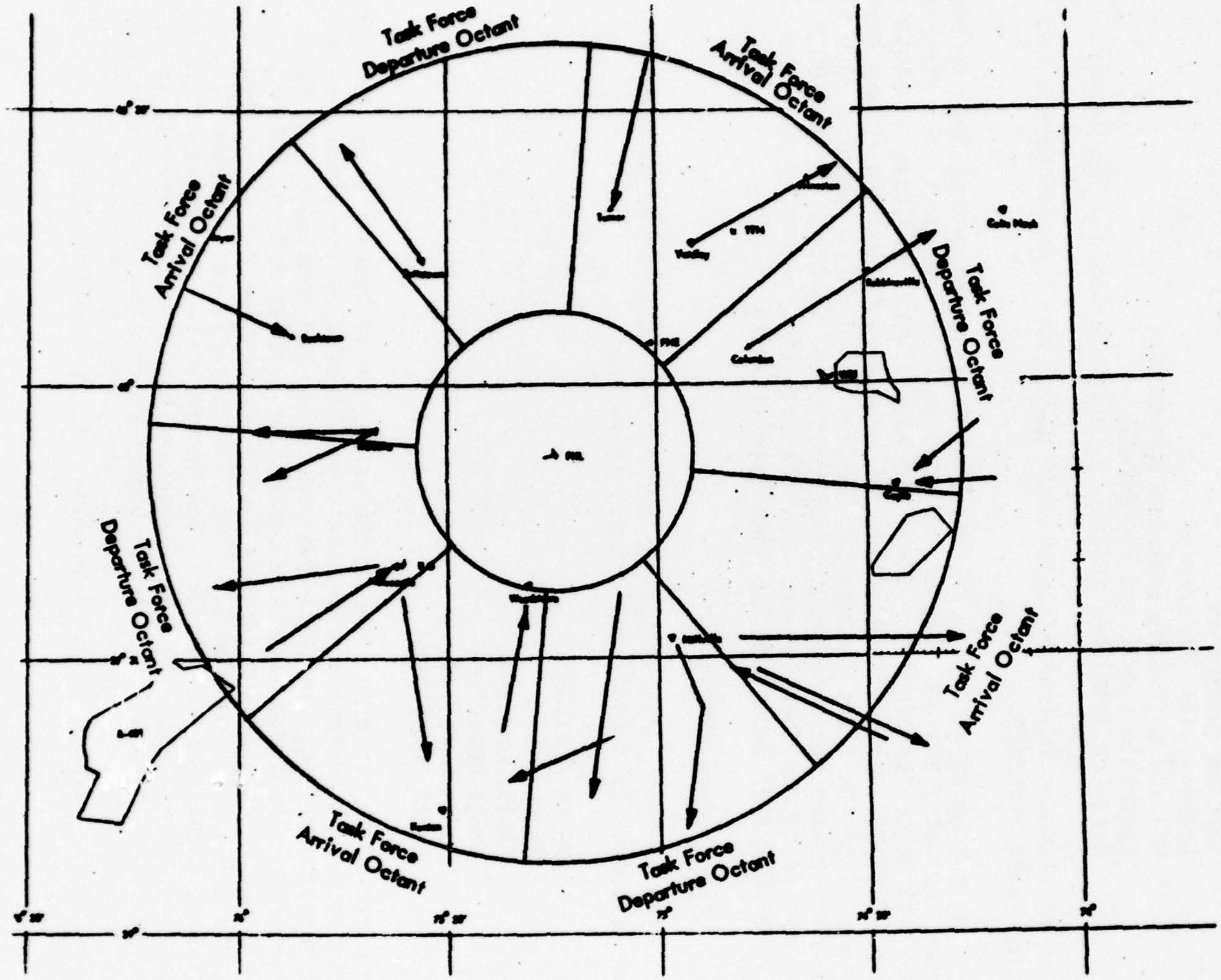


Figure 5.17 Current Philadelphia Traffic Flow vs. the Task Force Octant Concept

Modena (West)
Pottstown (Northwest)
Yardley (Northeast)
Robbinsville (Northeast)
Millville (South, East and Northeast)
Newcastle (South and Southwest)
North Philadelphia radial to Kenton (South and Southwest)

Numerous standard instrument departures (SIDs) and transitions are available to departing aircraft.

As a general rule, the PHL arriving traffic is kept at 6000 to 8000 feet at the arrival fixes and they are held above 5000 feet until the aircraft are within 15 nm of the airport. These procedures were developed to minimize noise problems. Aircraft departing PHL generally follow the runway heading (Runway 9) or the river (Runway 27, heading 255°) until reaching 2000 ft, then they turn toward their departure fix and proceed to climb to 6000-8000 feet for handoff to New York Center. Satellite traffic generally uses the altitudes of 2000-4000 feet except in the immediate vicinity of PHL.

Control Jurisdiction

The control jurisdiction for the Philadelphia TRACON is generally divided among six control positions. These are:

North Arrival
South Arrival
North Departure
South Departure
North Satellite
South Satellite

The north-south dividing line is the extension of Runways 9 and 27. Thus traffic arriving over Woodstown and Newcastle are handled by the South Arrival Controller and traffic arriving over Bucktown and Turner are handled by the North Arrival Controller. The North Departure Controller handles Modena, Pottstown and Yardley traffic while the South Departure Controller handles Millville departures, traffic using the Elmer-One SID (PNE 201° Radial), and Atlantic City and Baltimore Tower enroute traffic. The Robbinsville departures alternate between departure controllers with South Departure handling Robbinsville in the east configuration (Runway 9) and North Departure handling Robbinsville in the west flow (Runway 27). Of the satellites considered, North Satellite handles North Philadelphia, Trenton and Willow Grove. South Satellite handles Wilmington traffic.

Enroute Traffic Flow

In order to identify the enroute traffic flows, an analysis of the peak day IFR flights between city pairs which exchange 10 or more flights per day was undertaken. The low altitude traffic distribution is shown in Figure 5.18 and the high altitude traffic distribution is shown in Figure 5.19. About 65% of the

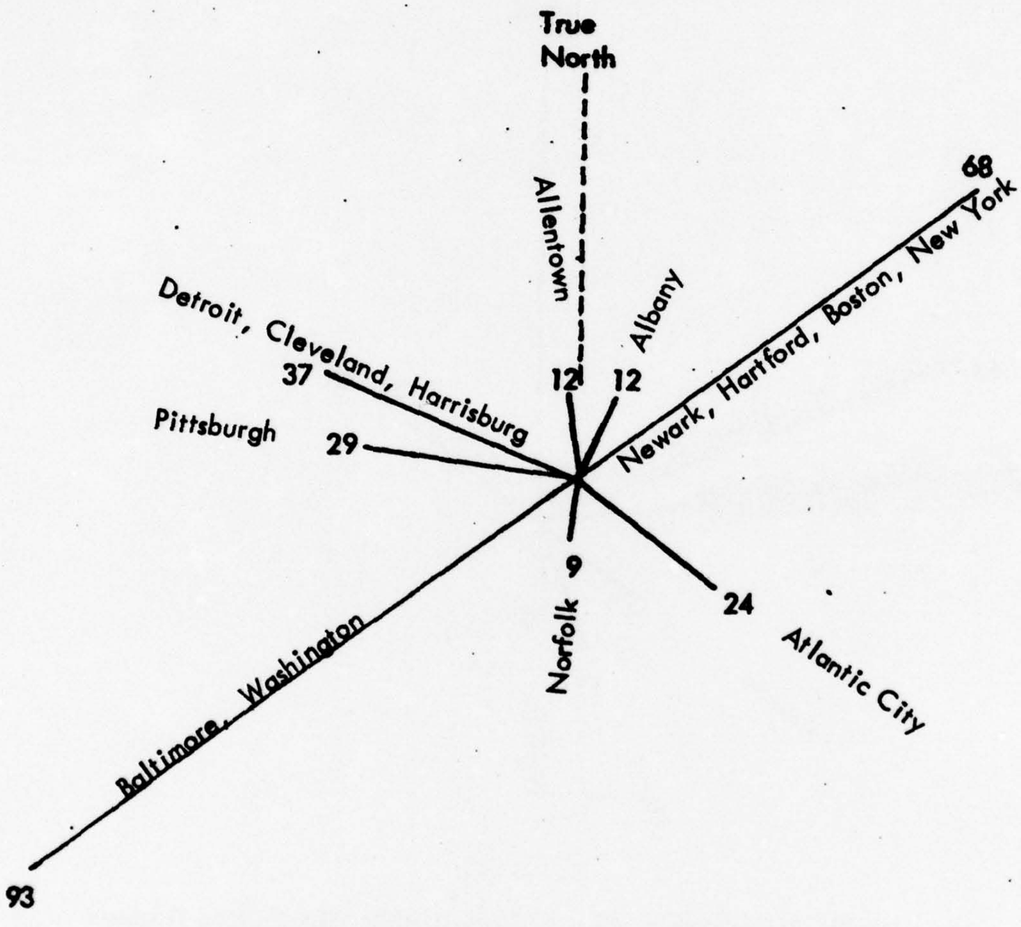


Figure 5.18 Philadelphia Low Altitude Traffic Distribution Diagram

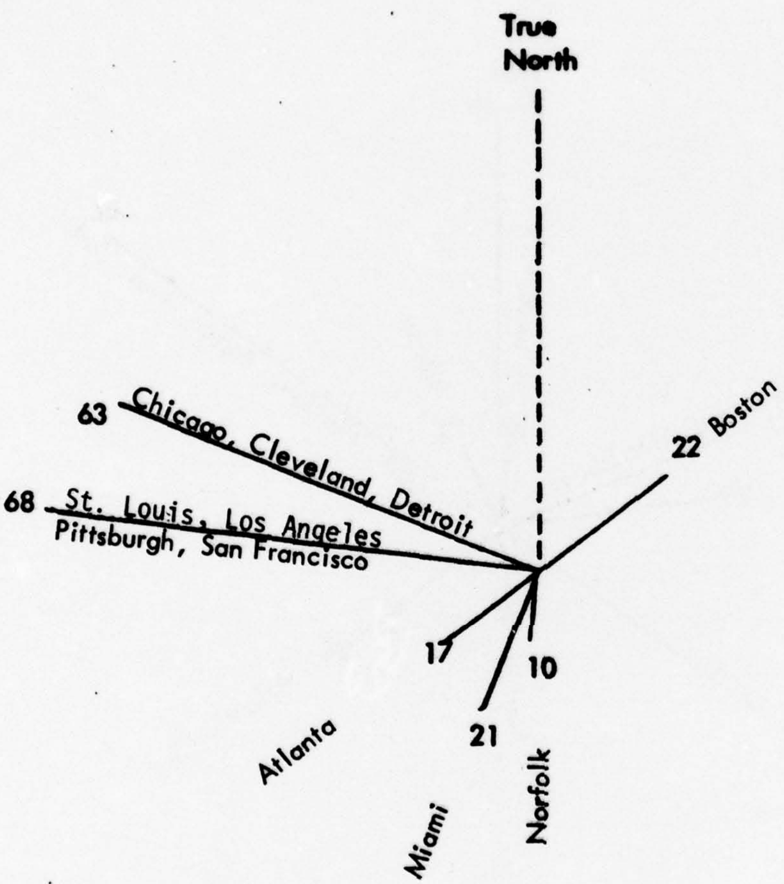


Figure 5.19 Philadelphia High Altitude Traffic Distribution Diagram

total Philadelphia traffic is depicted on these diagrams. Consequently, 35% of the Philadelphia traffic arrived from or went to places which exchanged less than ten flights per day with Philadelphia. The heavy low altitude flow in the southwest (93 flights) represents mostly Washington-Baltimore flights while the 68 flights to the northeast represents New York and Boston area traffic. The remaining major traffic is to the northwest and west-northwest (37 and 29 flights per day) and the southeast (24 flights per day with Atlantic City). The remaining traffic goes to the north (two 12 flight sectors) and the south (one 9 flight sector).

The high altitude traffic distribution is somwhat different than the low altitude distribution with the greatest concentration of traffic occuring in two west-northwest sectors (68 and 63 flights per day). The Boston traffic is represented by the 22 flights to the northeast. The remaining traffic is generally to the south with 17 flights to Atlanta, 21 flights to Miami and 10 to Norfolk.

5.1.3.2 The 1972 Philadelphia Terminal Area Design

Diagrams of the 1972 Philadelphia Terminal Area design are shown in Figures 5.20 and 5.21 (Runway 9 and 27 respectively). A description of the traffic flows and routes is contained in the following paragraphs.

<u>Arrivals - 1972</u>

The arrival fixes for the 1972 design are the same as those currently in use. They are:

Bucktown
Woodstown
Newcastle
Turner
Coyle - Woodstown

All arrivals entering the terminal area will pass over one of these fixes whether the aircraft is conventional or RNAV equipped. (Coyle is not a Philadelphia arrival fix as it is not in the Philadelphia approach control airspace. However, traffic arriving over Coyle is sent toward Woodstown and then vectored to the approach course at an appropriate point that varies with the runway in use.)

<u>East Flow (Figure 5.20)</u>

The traffic patterns for the east flow from the arrival fixes into the initial approach fix are essentially the same as those used today. Aircraft arriving over Bucktown proceed direct to the intermediate approach fix (IF). Since this is the highest density route, these aircraft were given a straight line route to the IF. Traffic arriving over Woodstown and Newcastle proceed direct to the IF also. The turn on angle for Woodstown traffic is slightly greater than 90° (110°) which may be undesirable from the pilots viewpoint.

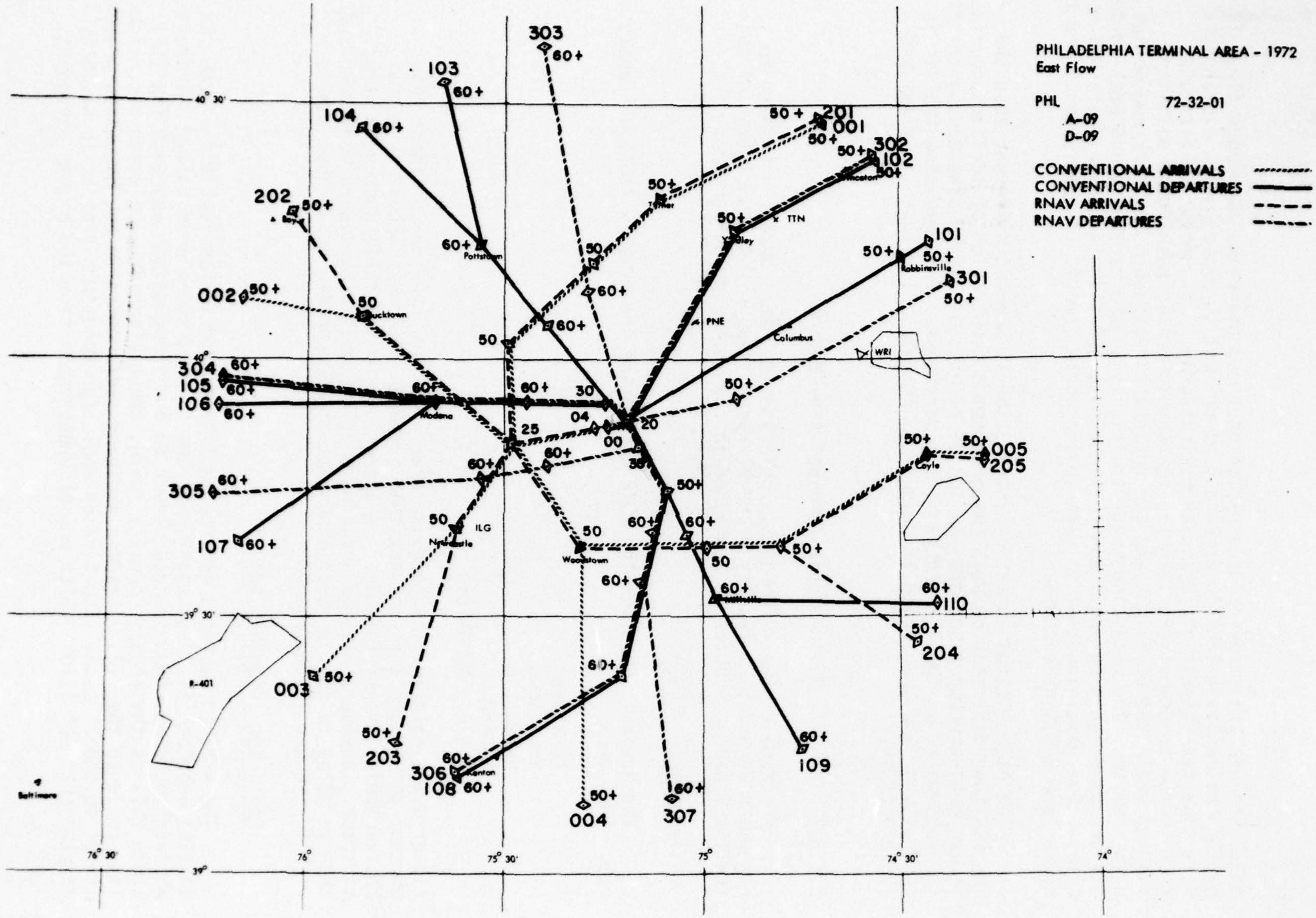


Figure 5.20 Philadelphia Terminal Area-1972 RNAV Routes, East Flow

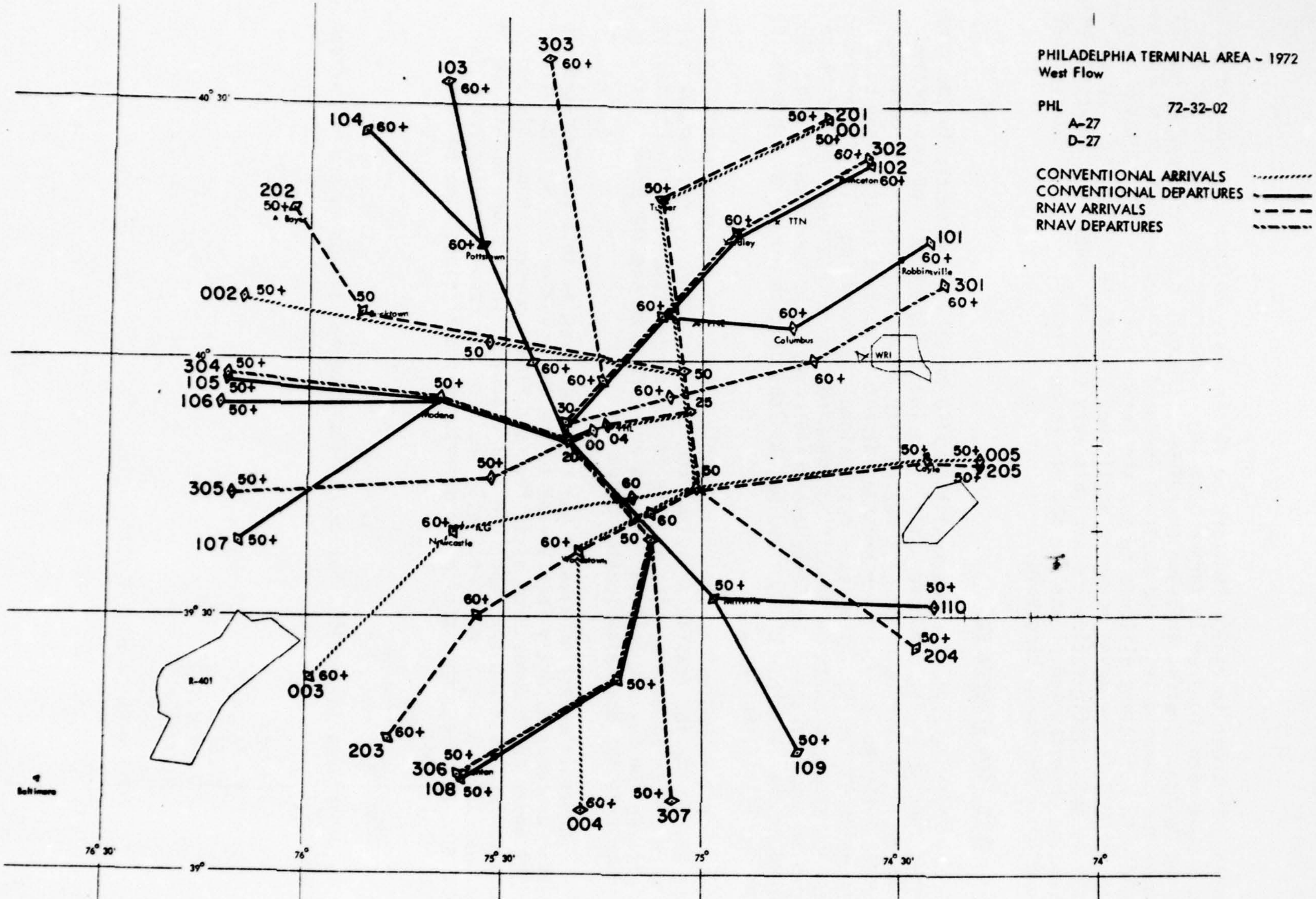


Figure 5.21 Philadelphia Terminal Area-1972 RNAV Routes, West Flow

However, in order to reduce the turn to 90° or less, another waypoint (or vector) would have been required to form a base leg. Consequently, the turn was left in the design. Traffic arriving over Turner proceeds to a left base by way of a modified downwind leg. The modified downwind was used so that north departures could gain sufficient altitude to top the Turner arrivals. All arrivals were kept at 5000 ft for noise purposes until they passed the feeder fix. In all cases in this configuration the arrivals were tunneled under the departures which permitted unrestricted climbs for the departing aircraft. The IWP was located 10 nm from the runway threshold.

West Flow (Figure 5.21)

Arriving traffic for the west flow also travel over essentially the same routes that are being used currently. The IWP for the west flow was located 10 nm from the threshold where it merged with both a left and right base leg. Traffic arriving over Bucktown proceeds direct to a point on the right base leg 5 nm north of the IWP. This is a conventional downwind leg. Traffic arriving over Woodstown proceeds on a modified downwind leg to intercept the left base leg 9 nm south of the IWP. Newcastle traffic and Coyle-Woodstown traffic also intercept the left base at the same point although each arrive at the base leg from opposite directions.

Note: Coyle is not within the Philadelphia TRACON and therefore cannot be used as a feeder fix for traffic arriving from that direction. Consequently, traffic is directed to Woodstown which is used as the feeder fix. Traffic conditions permitting the Coyle-Woodstown arrivals are turned to the IWP prior to reaching Woodstown in the West Flow configuration.

Turner Intersection lies on the right base leg in this configuration so traffic proceeds directly from Turner to the IWP. Turner and Bucktown arrivals tunnel under north departures as in the east flow. However, Newcastle and Woodstown arrivals top the departure to the south. This occurs mainly due to the departures being directed slightly south of the runway heading for noise abatement purposes, thus giving the departures insufficient time to reach a 6000 ft altitude.

Departures - 1972

Departures in the 1972 design use the same facilities as are in current use. These are:

Modena
Pottstown
Yardley
Robbinsville
Millville
New Castle
North Philadelphia 201° radial

East Flow (Figure 5.20)

All traffic climbs to 2000 ft on runway heading, then conventional traffic proceeds direct to one of the departure facilities mentioned above. RNAV departures generally follow the conventional routes until they attain 6000 feet and then they proceed to their appropriate low altitude departure fix. The need to accommodate conventional traffic in this design forces the RNAV traffic onto the conventional routes for some distance. This can be seen in the case of routes 108 and 307. If route 307 were permitted to proceed directly to the low altitude departure fix, it would then demerge from route 108 but later would cross route 108 again. This would create a controller problem in that a route 108 departure followed by a route 307 departure could be separated from each other at the demerge point but later conflict with each other at the crossing point. In order to prevent such occurrences, the RNAV traffic was then constrained to the conventional route until such time as they could be demerged and separated. However, on a few occasions this situation was permitted to occur such as on routes 107 and 305. In this case route 107 departs from the general flow of that octant so much that departures on route 305 would be excessively penalized if they had to remain clear of route 107 until they were out of the terminal area. Consequently, it was judged to be better to allow the routes to cross than to penalize the RNAV departure. A minor problem arises with routes 110 and 204. It can be seen in Figures 5.20 and 5.21 that these routes cross each other twice. This is not a desirable situation but one which apparently exists for low altitude traffic between Philadelphia and Atlantic City, New Jersey.

In the east flow configuration all departures were required to climb at a rate of 300 feet per mile up to 6000 feet so that they could top the arrivals at 5000 feet. Any aircraft that could not achieve that climb gradient would have to be held at 4000 feet and tunneled under the arrivals.

West Flow (Figure 5.21)

Departures climb to 2000 feet on a 255° heading for noise abatement purposes (following the river). Then conventional departures will proceed direct to their specified departure facility or radial. As with the east flow, the RNAV traffic will follow generally the same route as the conventional traffic until it is completely clear of the conventional traffic in order that the demerge-cross or demerge-merge discussed previously will not occur.

Departures to the north must attain a gradient of about 360 feet/mile up to 6000 feet in order to top arrivals from Bucktown. Otherwise they must be held at 4000 feet and tunnel under the arrivals. Departures to the south have insufficient distance to attain the 6000 ft. required for topping the arrivals, consequently, departures are tunneled under Woodstown and Newcastle arrivals.

Enroute Connecting Points

A brief description of each route and its enroute connection point is presented in the following section. Information on the current conventional routes came from current SIDs, STARs and preferred routes as found in the Airmen's Information Manual (AIM).

Arrivals - Conventional

001 - Victor 3 to Turner Intersection, arrivals from Newark and LaGuardia

002 - Victor 210 to Bucktown, principal arrival route from the West serving Buffalo, Chicago, Cleveland, Detroit, Pittsburg and Rochester

003 - Victor 433 to Newcastle VORTAC, arrivals from Baltimore/Washington area.

004 - Waterloo VORTAC direct to Woodstown VORTAC, arrivals from Norfolk and southern U.S. areas.

005 - Victor 312 to Coyle, Victor 312 to Woodstown, arrivals from New York Kennedy and Boston.

Departures - Conventional

101 - Victor 123, Columbus, Robbinsville, departures to New York LaGuardia and Kennedy.

102 - Victor 433 Yardley, Princeton, departures to Newark.

103 - Pottstown to East Texas VORTAC, departures to Buffalo, Rochester, Syracuse, Montreal.

104 - Pottstown to Pottstown 320° Radial to Victor 276, departures to Detroit and Chicago.

105 - Modena Five Departure, St. Thomas Transition departure to points west.

106 - Modena Five Departure to Bellaire, Front Royal, Newton and Westminister transitions, departure to points west.

107 - Modena, Victor 140, departure to Baltimore.

108 - North Philadelphia 201° radial to intercept Victor 16 (Kenton 063° radial) departure to Washington and points south.

109 - Millville, Millville 160° radial, Sea Isle 017° radial to Sea Isle, departure to Norfolk and points south.

110 - Millville, Millville 101° radial to Victor 139, departure to Boston or tower enroute to Atlantic City.

Arrivals - RNAV

201 - Overlies 001.

202 - RNAV arrival from the northwest arrival octant.

203 - RNAV arrival from the southwest arrival octant.

204 - RNAV arrival from the southeast arrival octant.

205 - Overlies 005.

Departures - RNAV

301 - RNAV departure to the northeast, parallels routes 101 and is offset 5 nm south.

302 - Overlies 102.

303 - RNAV departure to the north and northwest.

304 - Overlies 105.

305 - RNAV departure to the west, traffic goes south of the airport to reduce traffic congestion in the Modena and Bucktown areas.

306 - Overlies route 108.

307 - RNAV departure to the south.

5.1.3.3 The 1972 Task Force Concept at Philadelphia

Some of the traffic flows that are currently being used in the Philadelphia area are not in alignment with the arrival and departure octants described in the Task Force Report. As shown in Figure 5.17, the arrival fixes of Woodstown, Bucktown, and Turner fall in arrival octants. Also, the traffic arriving over Coyle and tower enroute traffic from Atlantic City arriving over Millville pass through the southeast arrival octant. Traffic arriving over Newcastle passes just inside a departure octant which is the major conflict with the octant pattern for arrivals.

Departing traffic over Pottstown, Newcastle, Robbinsville, Millville and the North Philadelphia 201° radial all fall within departure octants. Modena is on the boundary of a departure octant. The one major conflict with the octant concept is the departure over Yardley to Princton.

Traffic in the terminal maneuvering area departs somewhat from the Task Force concept however. Generally, arrivals from the downwind side of the airport are not routes near the airport. Instead arrivals follow a modified downwind approach which proceeds from the feeder fix to a point on the base leg approximately 10 nm from the final approach course. This generally does not restrict departures, however, as most departures are able to top the arrival traffic.

Some independent RNAV routes were developed for Philadelphia in the 1972-77 route structure. These routes were generally located in the terminal transition areas outside of the feeder fix and departure fix areas. The current radar vector/VOR routes served the higher density enroute traffic areas more directly in general, however. The RNAV departure route 305 was used to remove some of the departure traffic from the heavily traveled western routes 105, 106 and 107. Routes 305 and 107 are in conflict to the west of the airport. This conflict can be easily resolved by controller action if both routes are occupied since both routes can be under the jurisdiction of the same controller.

5.1.3.4 The Amended 1972 Philadelphia Terminal Area Design

In the original 1972 Philadelphia designs both VOR/vector and RNAV routes were depicted (Figures 5.20 and 5.21). After discussions with the Philadelphia controllers, it was determined that several of these RNAV routes presented significant operational problems. Consequently in the amended designs the independent RNAV routes were omitted and only RNAV routes which overlie the VOR/vector routes were used.

Several changes to the route structure were suggested by the terminal controllers. The amended designs are shown in Figures 5.22 and 5.23. Two arrival routes, 001 and 004, were added. Route 001 is a high altitude arrival route to Turner Intersection. Route 004 serves low altitude traffic from the east coast area.

Some changes to the route structures in the terminal maneuvering area were suggested. Route 003 in Figure 5.22 proceeds on a course from Coyle VORTAC direct to Newcastle VORTAC along V-312 until it intercepts the base leg approximately 10 miles southwest of the airport. This route was shown to be 5-6 miles south of route 003 in the initial design. Route 005 proceeds direct from Kenton VORTAC towards Woodstown VORTAC until it intercepts the base leg approximately 15 miles south of Philadelphia International Airport. In the initial design this route was shown as entering the terminal area at a point nearly south of Woodstown VORTAC.

In the west flow configuration similar changes were made in the terminal maneuvering area. Route 005 again proceeds direct from Kenton VORTAC to Woodstown VORTAC and then on a radar vector to intercept the downwind leg about 7 miles south of the airport. Arrivals over Coyle VORTAC on route 003 are given a vector from Coyle to intercept the localizer course 5 to 7 miles east of the airport. One change was also made to a departure route. Northeast departures using route 102 are given a 180° right turn and proceed directly to Columbus Intersection and then to Robbinsville VORTAC.

5.1.4 Miami

5.1.4.1 Characteristics of the Miami Terminal Area

The Miami terminal area is made up of one major airport, Miami International, one major satellite airport, Ft. Lauderdale-Hollywood International, and several

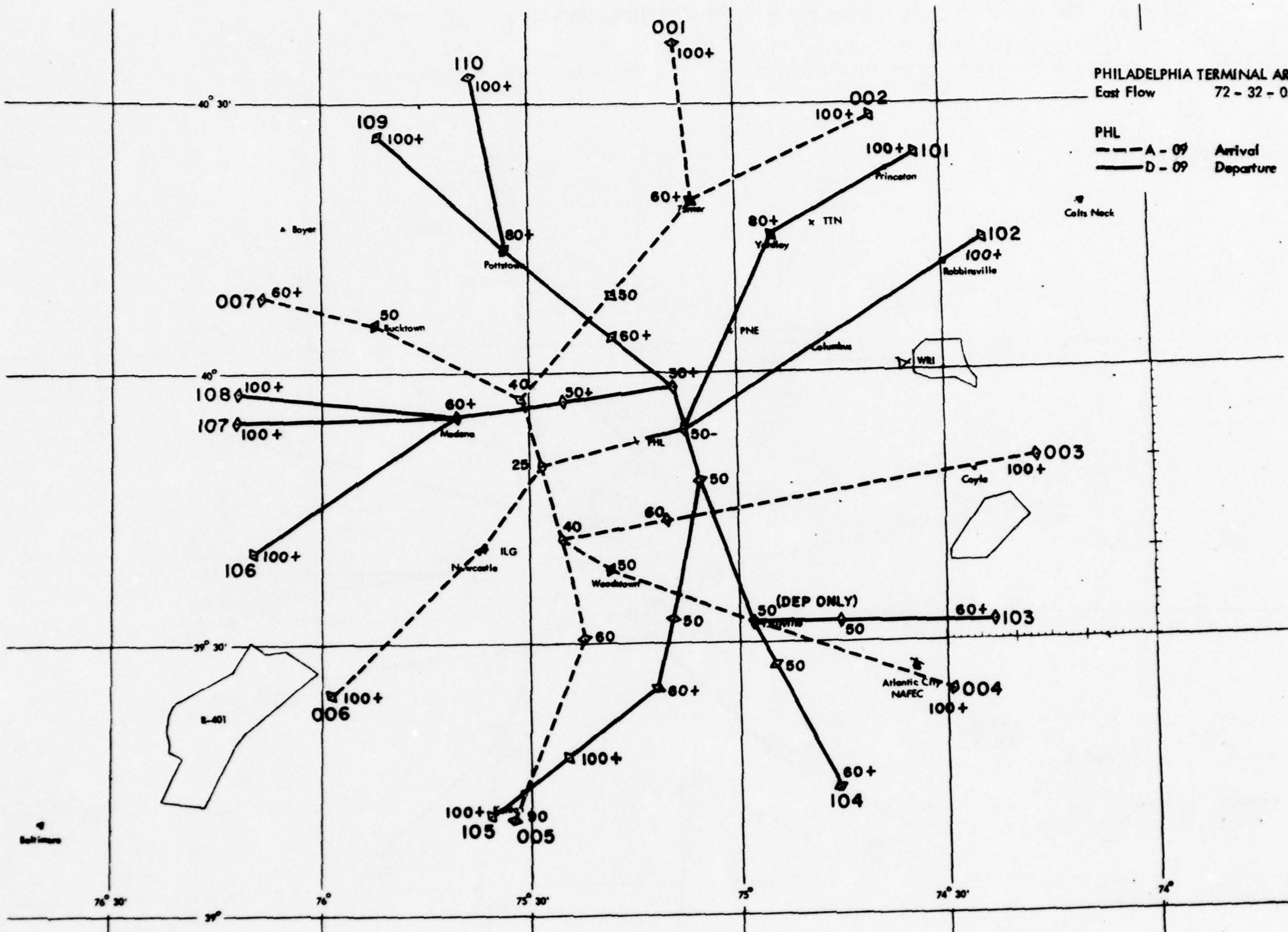


Figure 5.22 Amended Philadelphia Terminal Area - 1972 RNAV Routes, East Flow

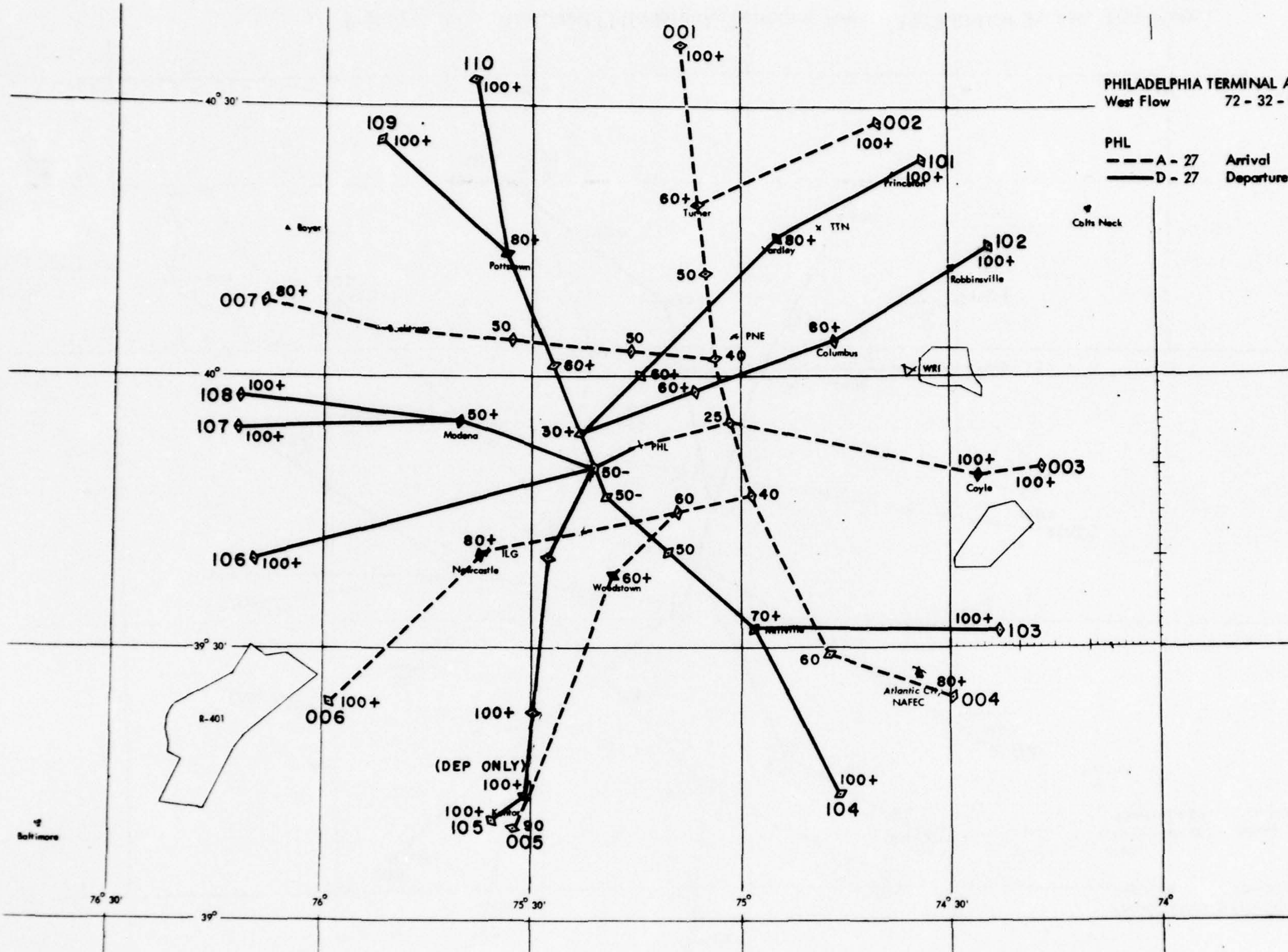


Figure 5.23 Amended Philadelphia Terminal Area - 1972 RNAV Routes, West Flow

smaller satellite airfields. The list of the Miami area airports is as follows:

Airport	Identifier
Miami International	MIA
Ft. Lauderdale-Hollywood International	FLL
Homestead AFB	HST
Opa Locka	OLF
Dade - Collier	TNT
Ft. Lauderdale Executive	FXE
New Tamiami	TMB
North Perry	HWO

The only two airports which generated significant IFR traffic are MIA and FLL. According to 1971 Peak Day statistics MIA had 801 instrument operations and FLL has 232 IFR operations. At MIA 32.8% of these operations were low altitude flights and 45.7% of the FLL flights were low altitude.

The terrain in the South Florida area is very flat and consequently terrain is no factor at either MIA or FLL.

Runway Orientation and Utilization

Airport diagrams of MIA and FLL are shown in Figures 5.24 and 5.25. The principal runways at MIA are 9L-27R and 9R-27L. At FLL the major runway is 9L-27R. Since the airports are on a north-south line and the runways are in an east-west direction these two airports can operate independently without interference from one another.

The east flow at Miami is prevalent with about 2/3 of the operations. The west operation is used the other 1/3 of the time. Some operations have been instituted at MIA using runway 12-30 for departures. These were not considered in the terminal design however. The configurations that were selected for RNAV terminal design at MIA and FLL were as follows:

CONFIGURATION	MIAMI		FORT LAUDERDALE	
	Land	Depart	Land	Depart
1	09L & 09R	09L & 09R	09L	09R
2	27R & 27L	27R & 27L	27R	27L

Present traffic flows in the MIA area are shown in Figure 5.26. The major traffic flow arrives over either New River or Pike intersection in the northwest and northeast respectively. Other arrival areas are Wahoo - southeast, Flamingo - southwest, Ranger - southwest and Westland - Northwest. Departure gates include Oakland and Bradley to the north, Nimrod to the northeast, Pineapple to the east, Cutler to the southeast, Perrine to the southwest, Vega to the west (little used), Cypress to the northwest and Homestead to the south. It can be seen from the octant overlay of Miami that the current traffic flow in the heavily traveled north direction is in general agreement with the octant concept. The one

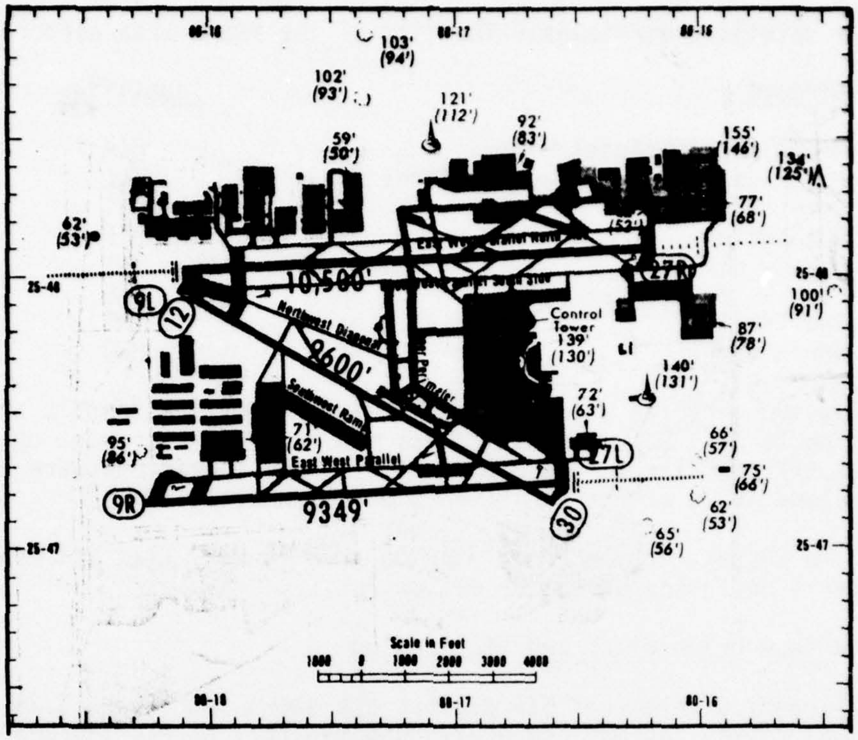


Figure 5.24 Miami Airport Configuration

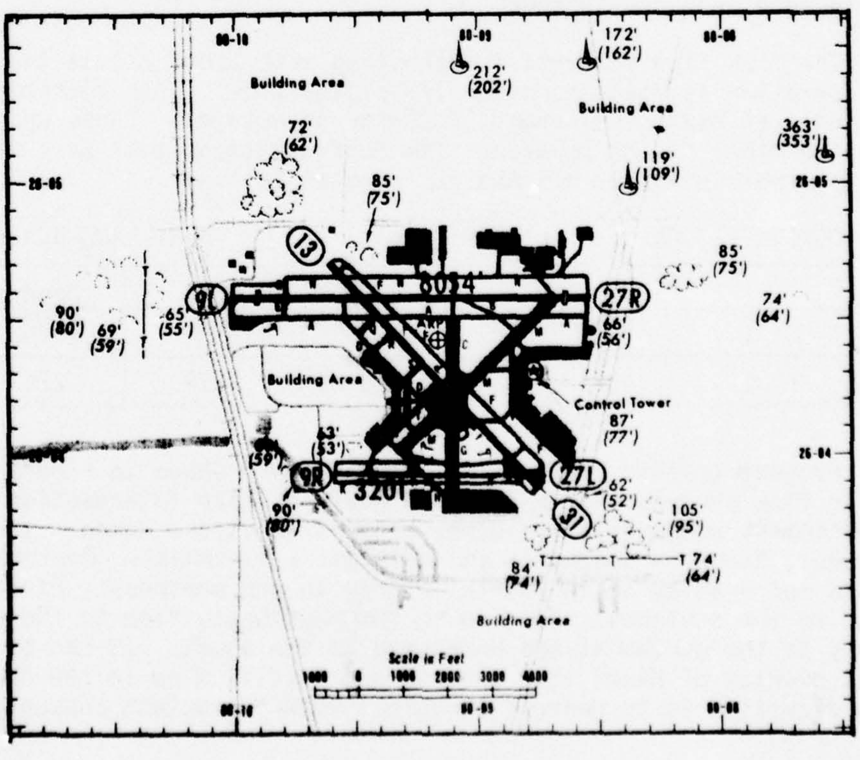


Figure 5.25 Fort Lauderdale Airport Configuration

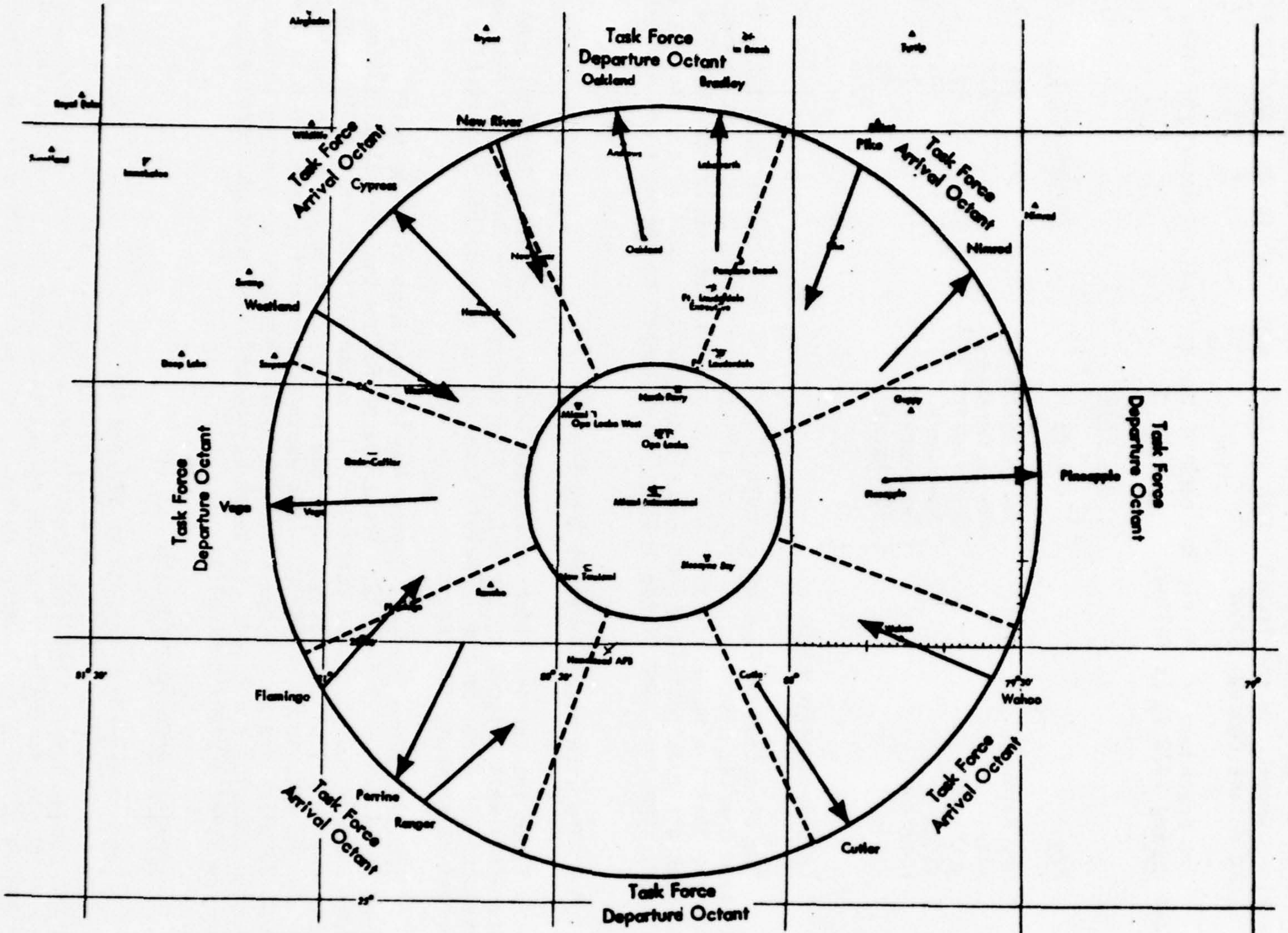


Figure 5.26 Current Miami Traffic Flow vs. the Task Force Octant Concept

exception in the primary traffic flow areas is in the Cypress and Nimrod departure areas. In the lightly used southern direction several conflicts with the octant concept occur.

The breakdown of traffic for each of the arrival and departure fixes at Miami during 1972 is as follows:

Arrivals

Fix	Area	Percentage of Traffic
New River	North, northwest	31%
Pike	North, northeast	22%
Westland	Northwest	20%
Wahoo	Southeast	16%
Flamingo	Southwest	7%
Ranger	Southwest	4%
		100%

Enroute Traffic Flow

The direction of flow of enroute traffic is depicted on the high and low altitude traffic distribution diagrams (Figures 5.27 and 5.28). It is readily apparent that the major traffic flow is to and from the north for both low and high altitude traffic. Some low altitude traffic goes to the east to the Bahamas. The remainder of the traffic is scattered to the west and northwest.

5.1.4.2 The 1972 Miami Terminal Area Design

Since the current radar vector/VOR routes in the Miami terminal area are moderately well aligned to the octant flow concept, the RNAV routes that were developed for Miami in the 1972-1977 time period were designed to overlie the current radar vector/VOR routes.

The 1972 Miami Terminal Design for low and high altitude traffic is shown in Figures 5.29 to 5.32. These routes follow the general direction of radar and VOR routes in use currently. No major altitude restrictions are necessary in any of the designs with the possible exception of the FLL route 104 to the west in Figure 5.30. This route is restricted to 5,000 feet for about 25 miles due to MIA-New River arrivals. However, this route is not heavily traveled and higher altitudes may be obtained through coordination with the New River arrival controller.

Terminal Area Traffic Flow

Most of the north traffic to MIA and FLL arrive or depart the terminal area on either a Miami VORTAC or a Key Biscayne VORTAC radial. Upon arriving at the feeder fix conventional arrivals are vectored to the final approach course by the controller. The RNAV routes have been established in the close proximity of these radar vector routes. The traffic patterns in the terminal

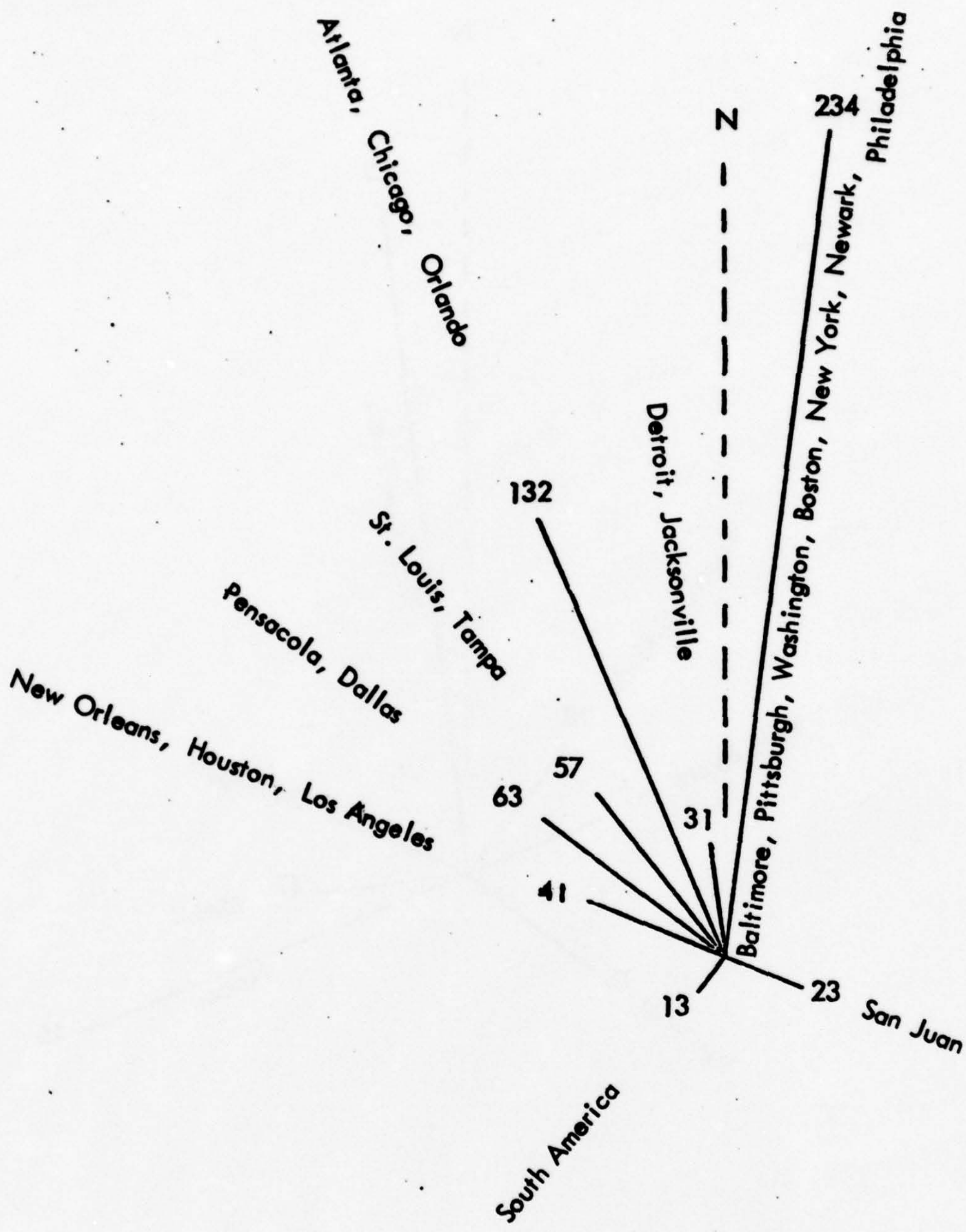


Figure 5.27 Miami High Altitude Traffic Distribution Diagram

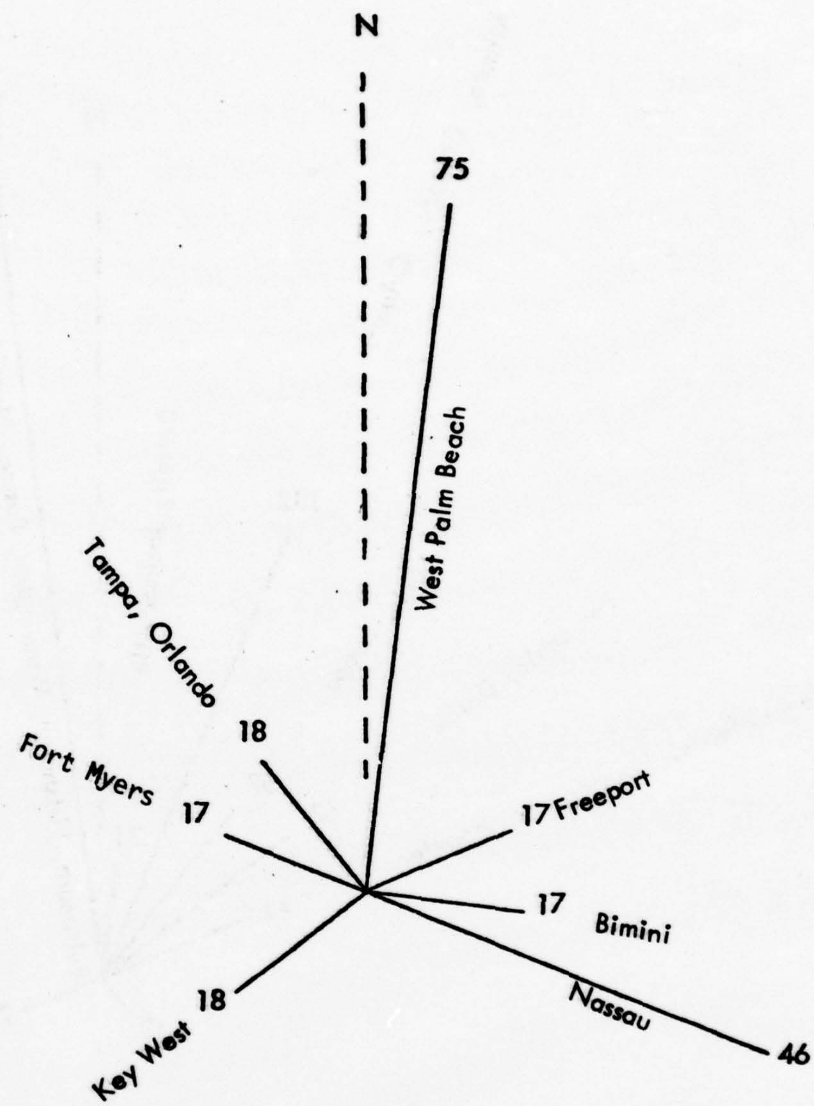


Figure 5.28 Miami Low Altitude Traffic Distribution Diagram

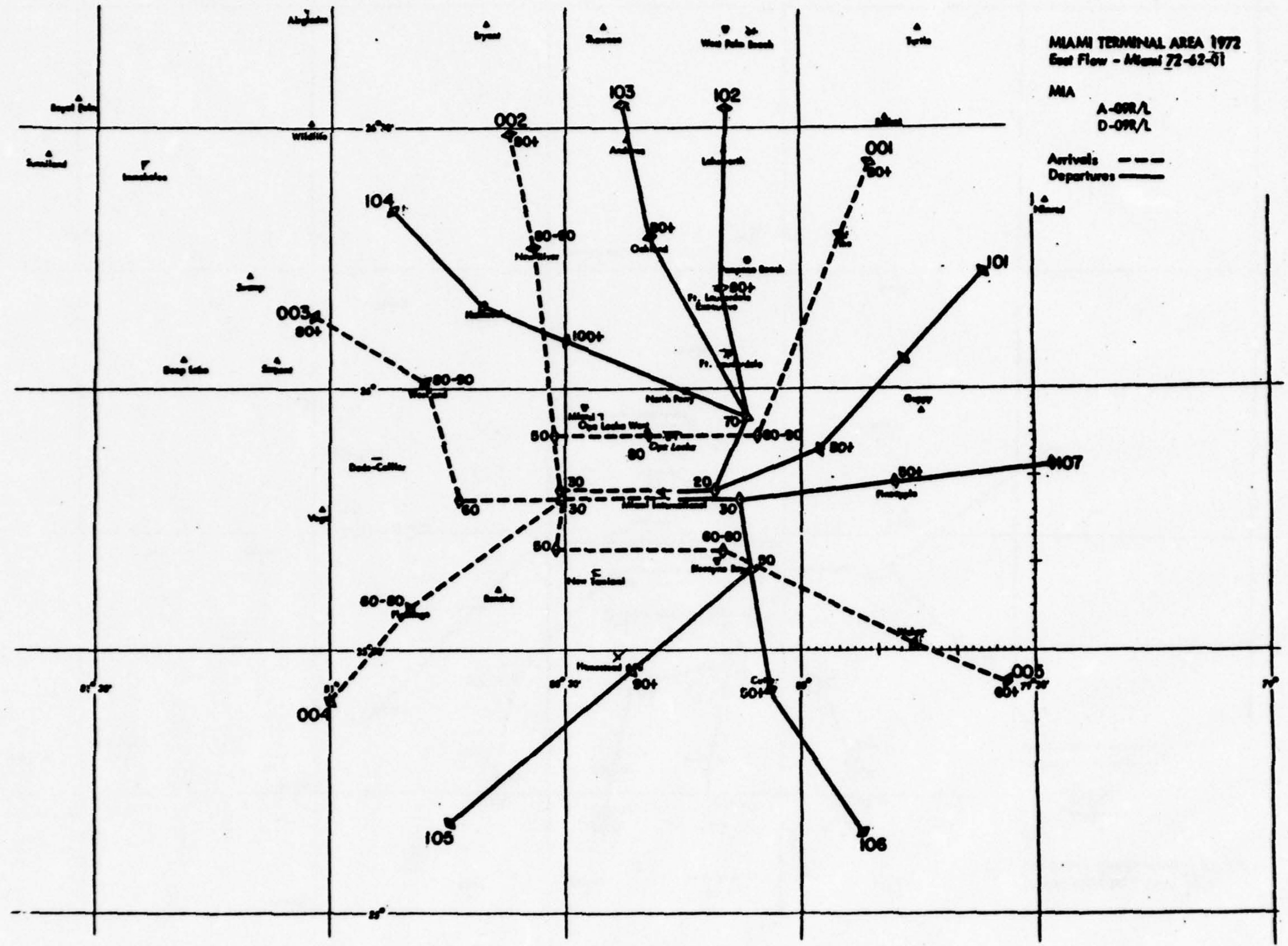
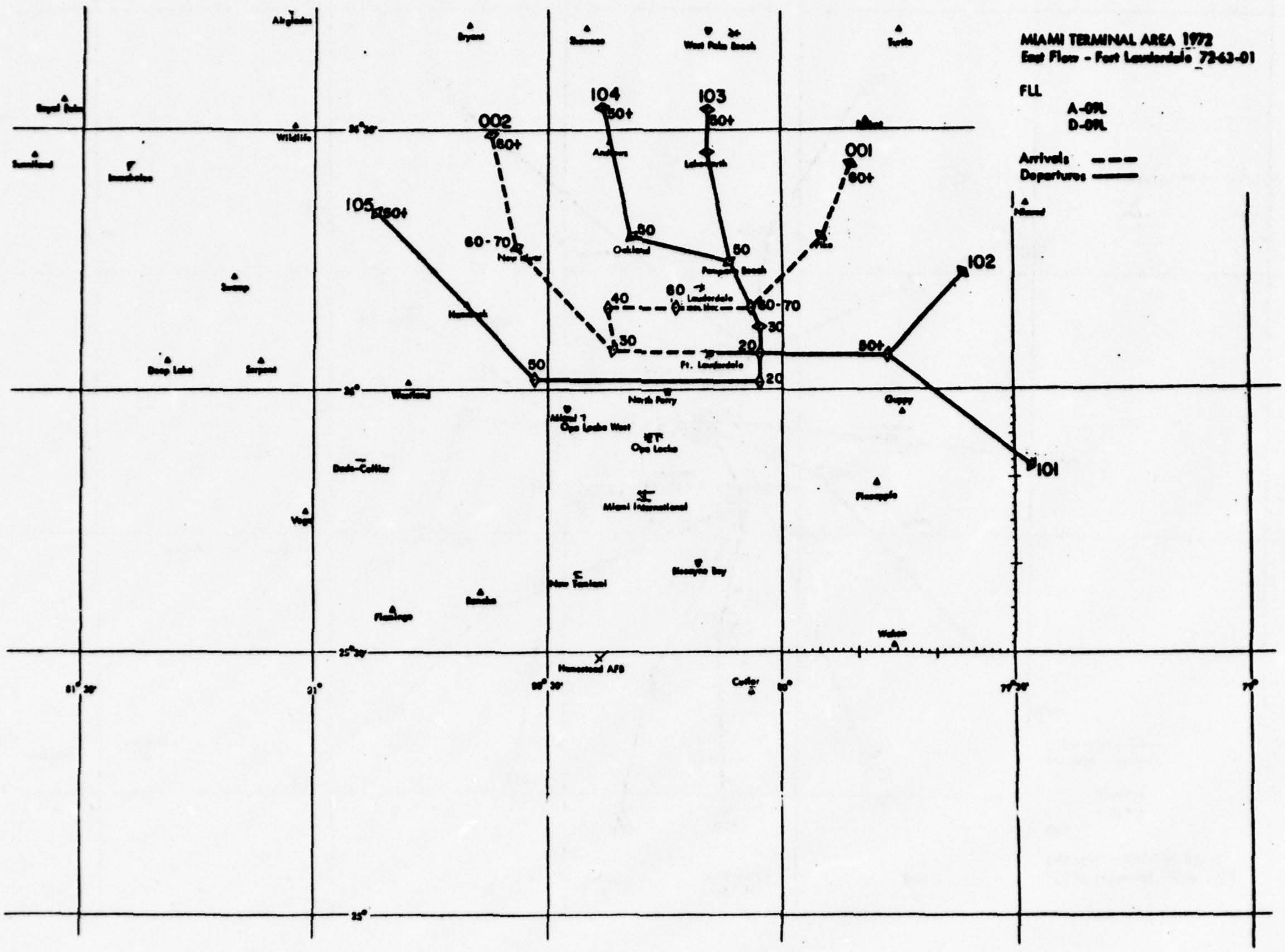


Figure 5.29 Miami Terminal Area - 1972 RNAV Routes, Miami, East Flow


MIAMI TERMINAL AREA 1972
East Flow - Fort Lauderdale 72-63-01
FLL
A-09L
D-09L
Arrivals
Departures
001
002
101
102
103
104
105
Ft. Lauderdale
Miami International
Opa Locka
Homestead AFB
Figure 5.30 Miami Terminal Area - 1972 RNAV Routes, Fort Lauderdale, East Flow

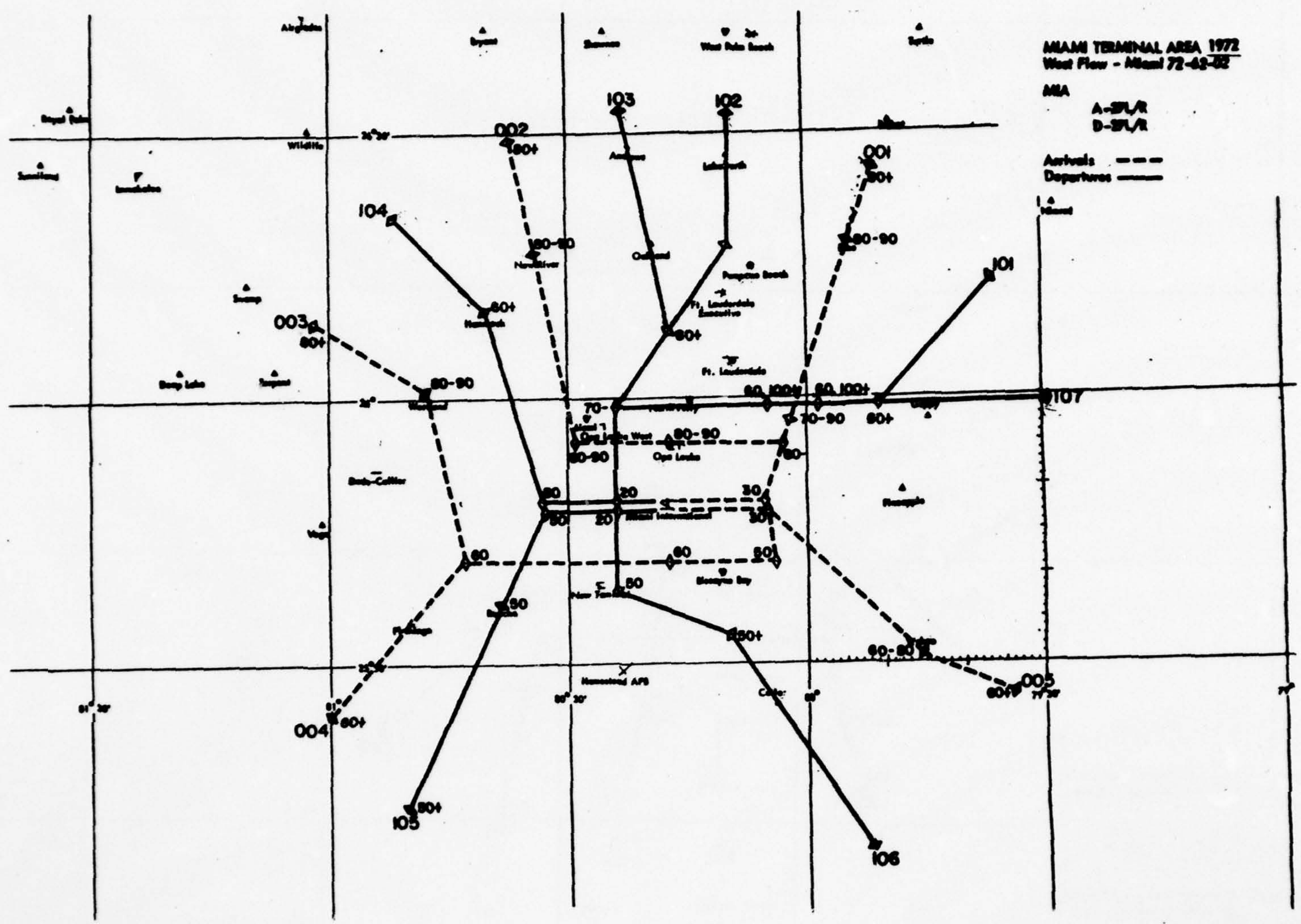


Figure 5.31 Miami Terminal Area - 1972 RNAV Routes, Miami, West Flow

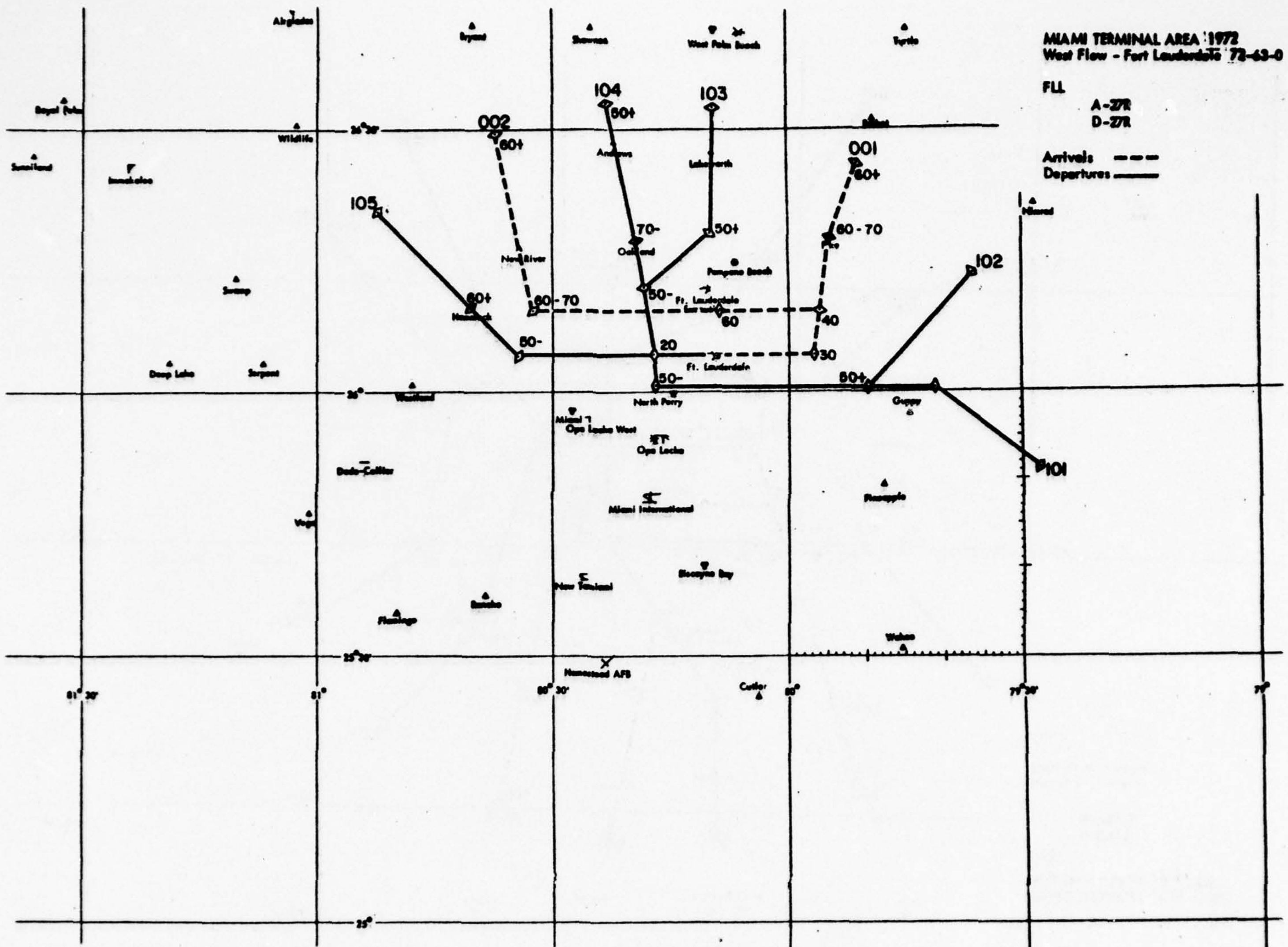


Figure 5.32 Miami Terminal Area - 1972 RNAV Routes, Fort Lauderdale, West Flow

maneuvering area at both Miami and Fort Lauderdale are the conventional downwind, base and final maneuvers. The use of the parallel runways at Miami permits some flexibility in handling arrivals from the several feeder fixes. Figures 5.29 and 5.31 depict only one of several possible feeder fix - runway combinations that may be used at Miami.

Both MIA and FLL make use of the Pike and New River feeder fixes for the heavy arrival flow from the North. Due to the location of the two airports the MIA and FLL arrivals and departures are separated by altitude. Consequently crossing routes are not a major problem in the Miami terminal area in either the east flow or the west flow configuration.

5.1.4.3 The 1972 Task Force Concept at Miami

The traffic flow at Miami is moderately compatible with the octant flow concept in the high density traffic areas on the northern side of the terminal area. Some of the arrival and departure sectors are not quite the same size as those suggested by the Task Force, but the flow pattern is essentially similar except for the Cypress departures to the northwest which split the arrival sector formed by Westland and New River and the Nimrod departures which cross the Pike arrival area. The areas to the south of Miami do not generally follow the octant flow but their traffic flow is extremely light.

The traffic patterns in the terminal maneuvering area are a classical example of the Task Force Model. Arrivals are kept close to the airport when approaching from the downwind side of the airport in order to permit departures to climb rapidly to their cruise altitude.

In general, the 1972-1977 Miami RNAV routes are quite well aligned with the Task Force terminal area concept in the major traffic flow directions.

5.1.4.4 The Amended 1972 Miami Terminal Area Design

Controller comments on the 1972 Miami terminal area designs centered primarily on route locations and separation procedures in the vicinity of the airport. Comments on the separation procedures concerned the departure aircraft. The Terminal Area Handbook 7110.8D requires a 45° divergence after take-off when simultaneous departures on parallel runways are in use. This modification has been made in both of the amended traffic flows (Figures 5.33 and 5.34).

In the east flow configuration, Figure 5.33, two of the departure routes were moved slightly to be more compatible with the Miami VOR/radar vector procedures. Departures to the east, route 103, were moved north to Guppy Intersection. Departures to the southwest were shown as overlying Homestead Air Force Base in the original design. This route, number 106, was moved slightly east to conform with the existing procedures. This procedure calls for the controller to issue a radar vector to Marathon Intersection which is beyond the extent of the map in Figure 5.33.

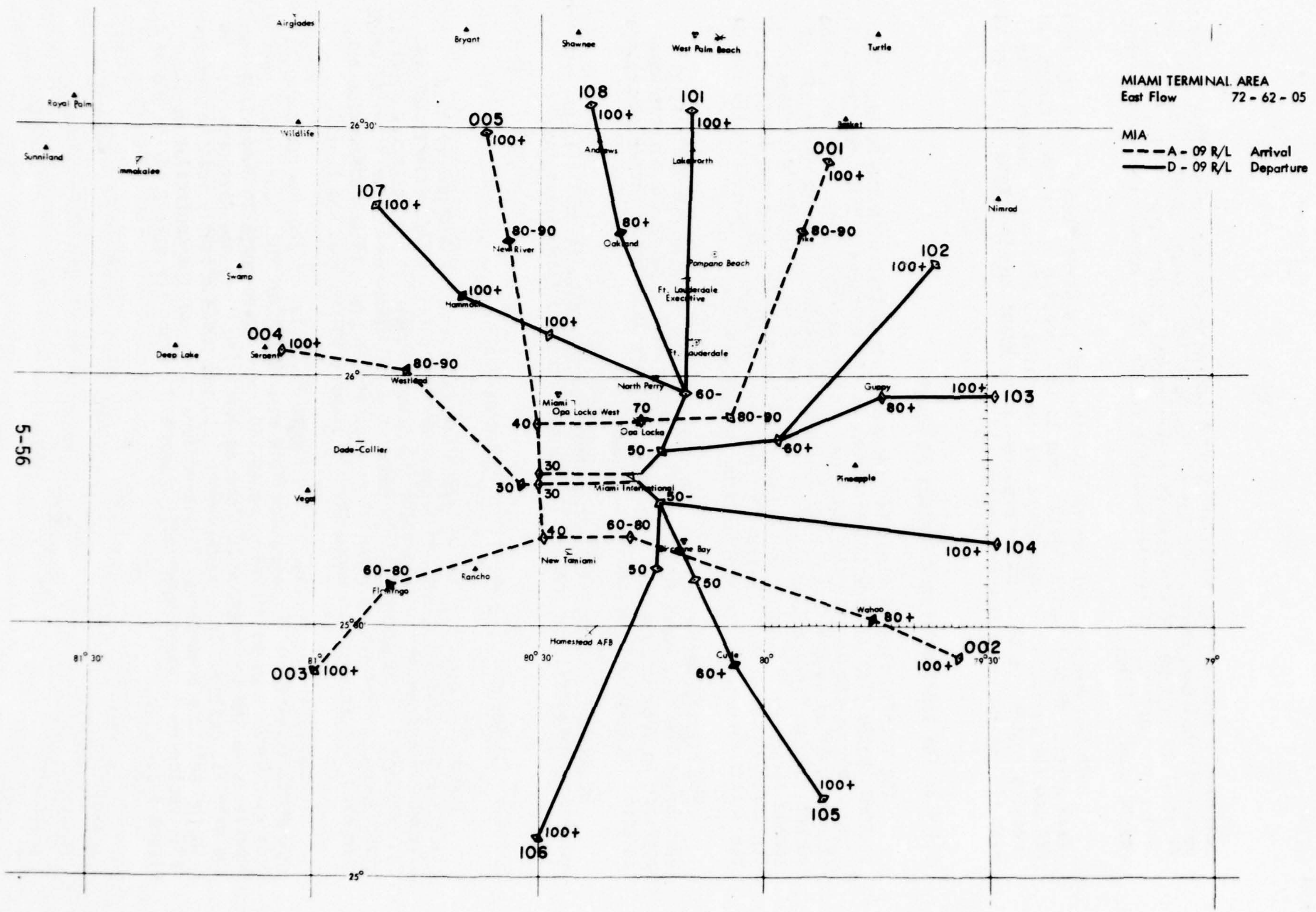


Figure 5.33 Amended Miami Terminal Area-1972 RNAV Routes, East Flow

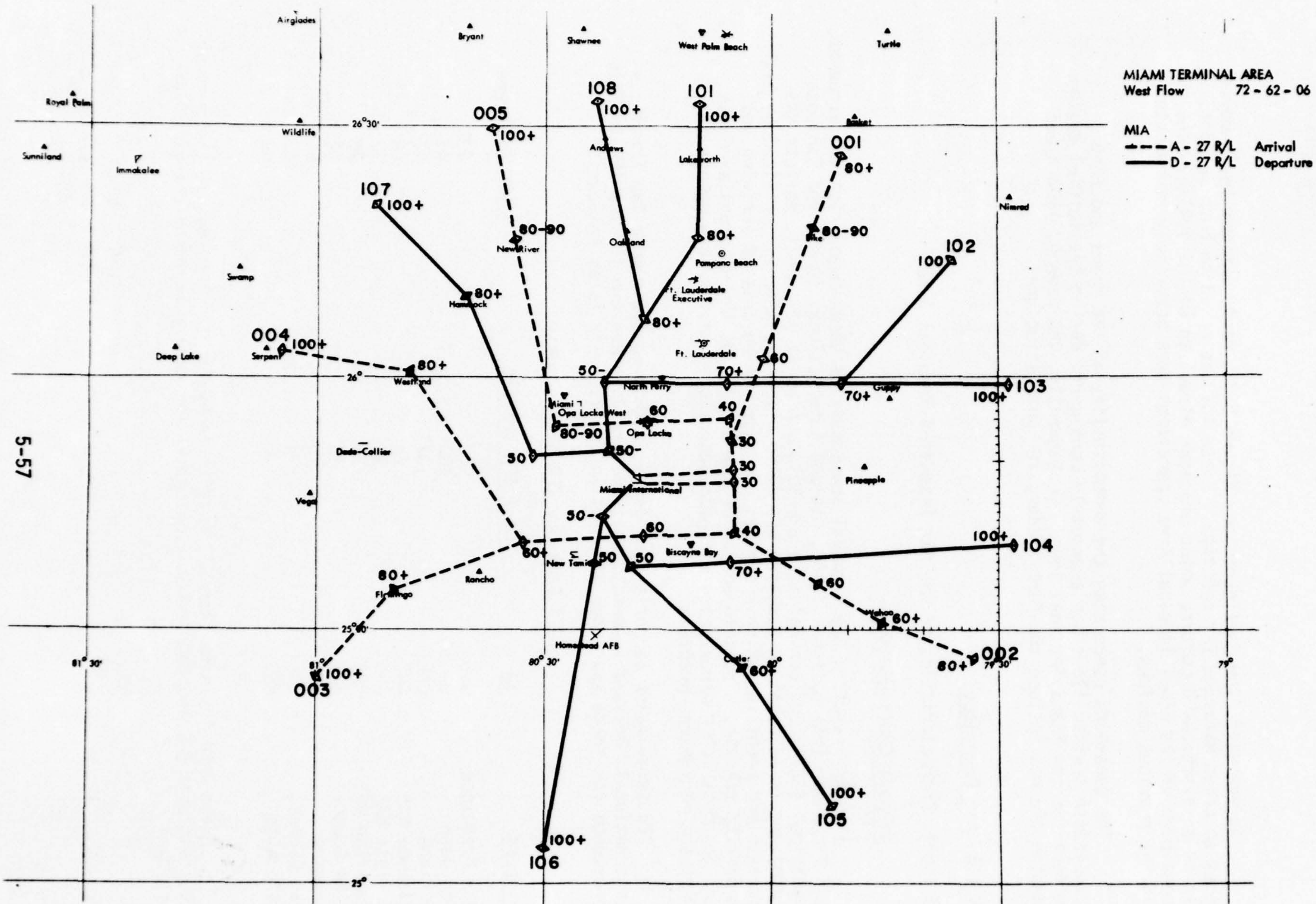


Figure 5.34 Amended Miami Terminal Area-1972 RNAV Routes, West Flow

In the west flow configuration, Figure 5.34, route 106 was again moved east to cross Marathon Intersection. Route 104 was added to both designs. It is an eastbound departure which proceeds direct to Bimini VORTAC. The remainder of the Miami Terminal Area operations were accurately represented in the previous designs.

The questions concerning the compatibility of the Miami and Fort Lauderdale traffic flows was adequately considered during the initial design effort for the Miami Terminal area. Consequently, the amended 1972 Miami design did not include the Fort Lauderdale route structures.

5.1.5 San Francisco

5.1.5.1 Characteristics of the San Francisco Terminal Area

Airport Configuration

The San Francisco Bay terminal area contains three major civilian airports, San Francisco International (SFO), Oakland International (OAK), and San Jose Municipal (SJC), and two military airfields, Alameda NAS (NGZ), Moffett NAS (NUQ) and is adjacent to Hamilton AFB (SRF). The bay area is contained by high terrain and mountains which restricts the maneuvering area of arriving and departing traffic. The interaction of the traffic of the numerous airports and the restricted maneuvering airspace generate a considerable number of airspace management problems.

The three major airports considered in this analysis were San Francisco International, Oakland International, and San Jose Municipal. The IFR traffic breakdown for these and other airports in the vicinity is as follows:

1971 Peak Day IFR Operations

Airport	ID	Total IFR Traffic	% Low Altitude
San Francisco	SFO	932	23%
San Jose	SJC	183	41
Oakland	OAK	137	47
Alameda NAS	NGZ	75	64
Moffett NAS	NUQ	52	37
Hamilton AFB	SRF	29	28
NAPA County	APC	12	92
Hayward	HWD	10	90
San Carlos	SQL	8	100
Palo Alto	PAO	6	100

These data indicate that SFO traffic is by far the heaviest at the present time and that SJC and OAK have the potential for generating more traffic than is shown.

Runway Orientation and Utilization

Airports in the area are generally located on the rim of the bay and runways are primarily aligned in a northwest-southeast manner which aids in establishing a compatible traffic flow. Airport diagrams for SFO, SJC and OAK are shown in Figures 5.35, 5.36 and 5.37. The runways at OAK and SJC that are used primarily for both arrivals and departures are those in the northwest or southeast direction. However, at SFO, in order to alleviate some of the noise problems, Runway 28L is used for arrivals and Runway 1 R/L for departures, which allows aircraft to make their approach and initial climb over the waters of San Francisco Bay. This runway combination is used 70% of the time with the remaining time equally divided in the use of runways 28 for arrivals and departures and Runway 19L for arrivals and Runway 10R/L for departures. Data for runway utilization of OAK and SJC was not available.

The runway configurations selected for design consideration are shown in the following table:

RUNWAY CONFIGURATION USED

Airport	West Flow Configuration 1		Southeast Flow Configuration 2	
	Land	Depart	Land	Depart
SFO	28L	01 R/L	19L	10 R/L
OAK	29	29	11	11
SJC	30L	30L	12R	12R

Use of runway configuration 2 is avoided when possible since the paths of San Francisco and Oakland arrivals cross on final approach. This creates a low arrival rate for both airports.

Traffic Flows

Terminal area traffic flows for all three major airports in the Bay area are shown in Figure 5.38 in comparison with the Task Force octant concept. An interesting feature of the present traffic management in the Bay area is that prop and jet traffic patterns often meet over a feeder fix but then follow different ground tracks to the final approach fix.

As can be observed by looking at the traffic distribution diagrams for the Bay area (Figures 5.39 and 5.40) the dominant high altitude traffic flow is in the east-northeast direction to New York and Chicago and in the southeast to Los Angeles. The dominant low altitude traffic pattern is southeast along the coast and northeast to Sacramento.

5.1.5.2 The 1972 San Francisco Terminal Area Design

The 1972 terminal area designs for San Francisco depicted in Figures 5.41. to 5.46 are essentially the present VOR and radar routes in use currently. It

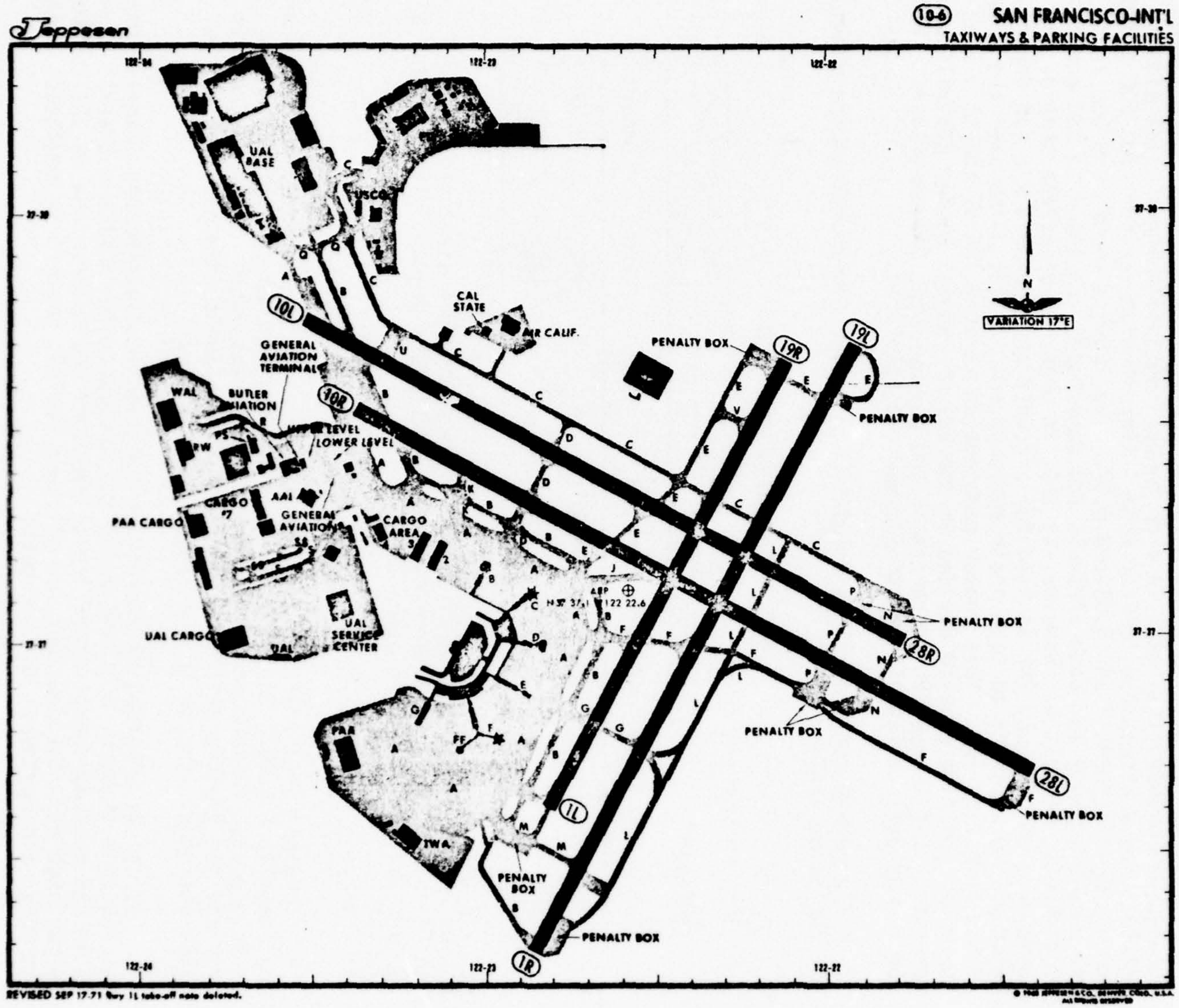


Figure 5.35 San Francisco Airport Configuration

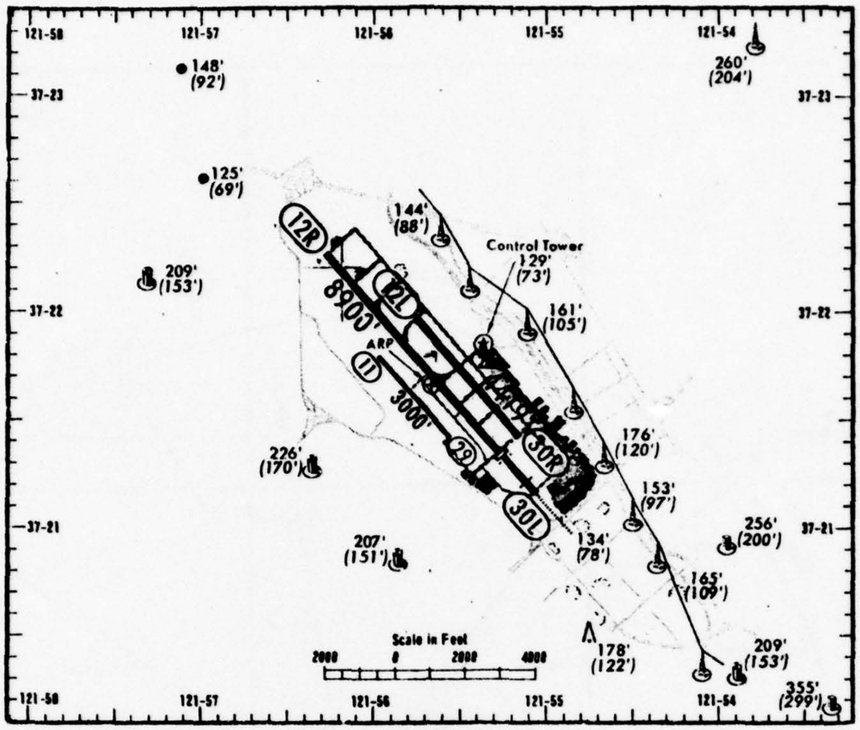


Figure 5.36 San Jose Airport Configuration

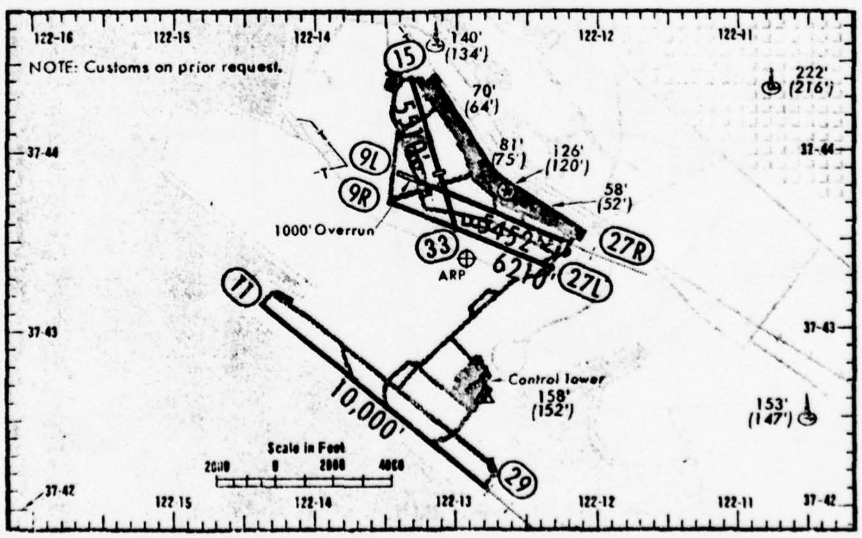


Figure 5.37 Oakland Airport Configuration

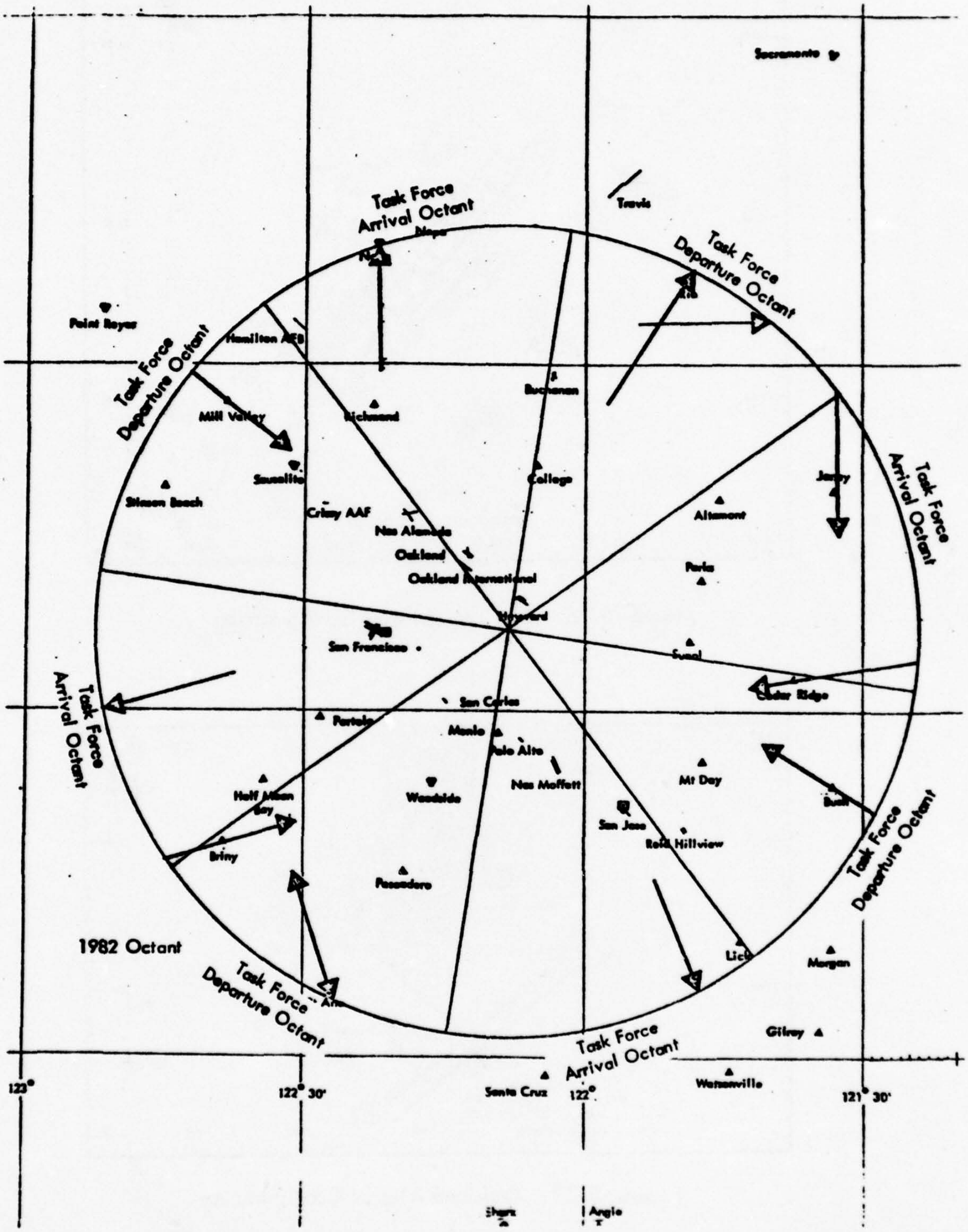


Figure 5.38 Current San Francisco Traffic Flow vs. the Task Force Octant Concept

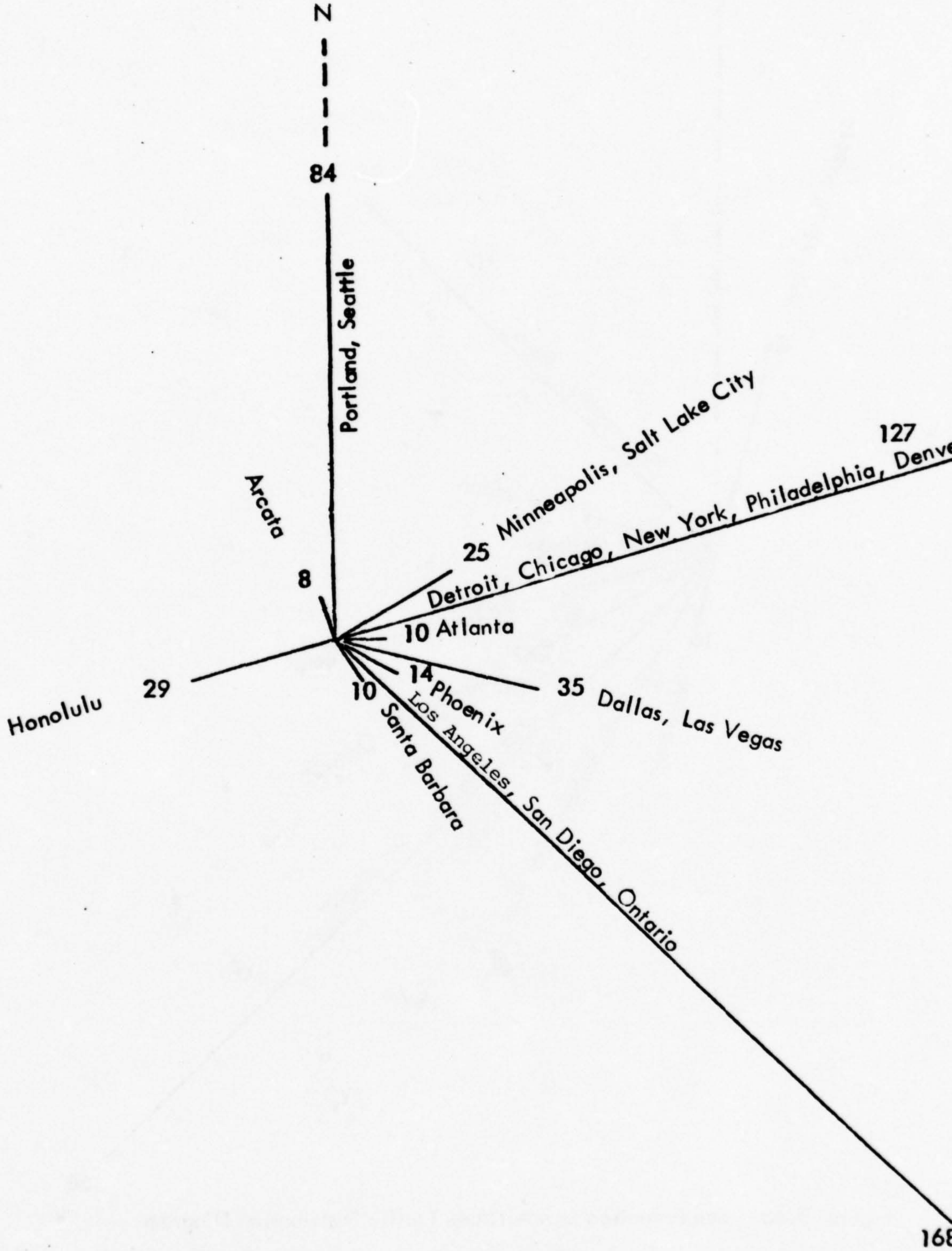


Figure 5.39 San Francisco High Altitude Traffic Distribution Diagram

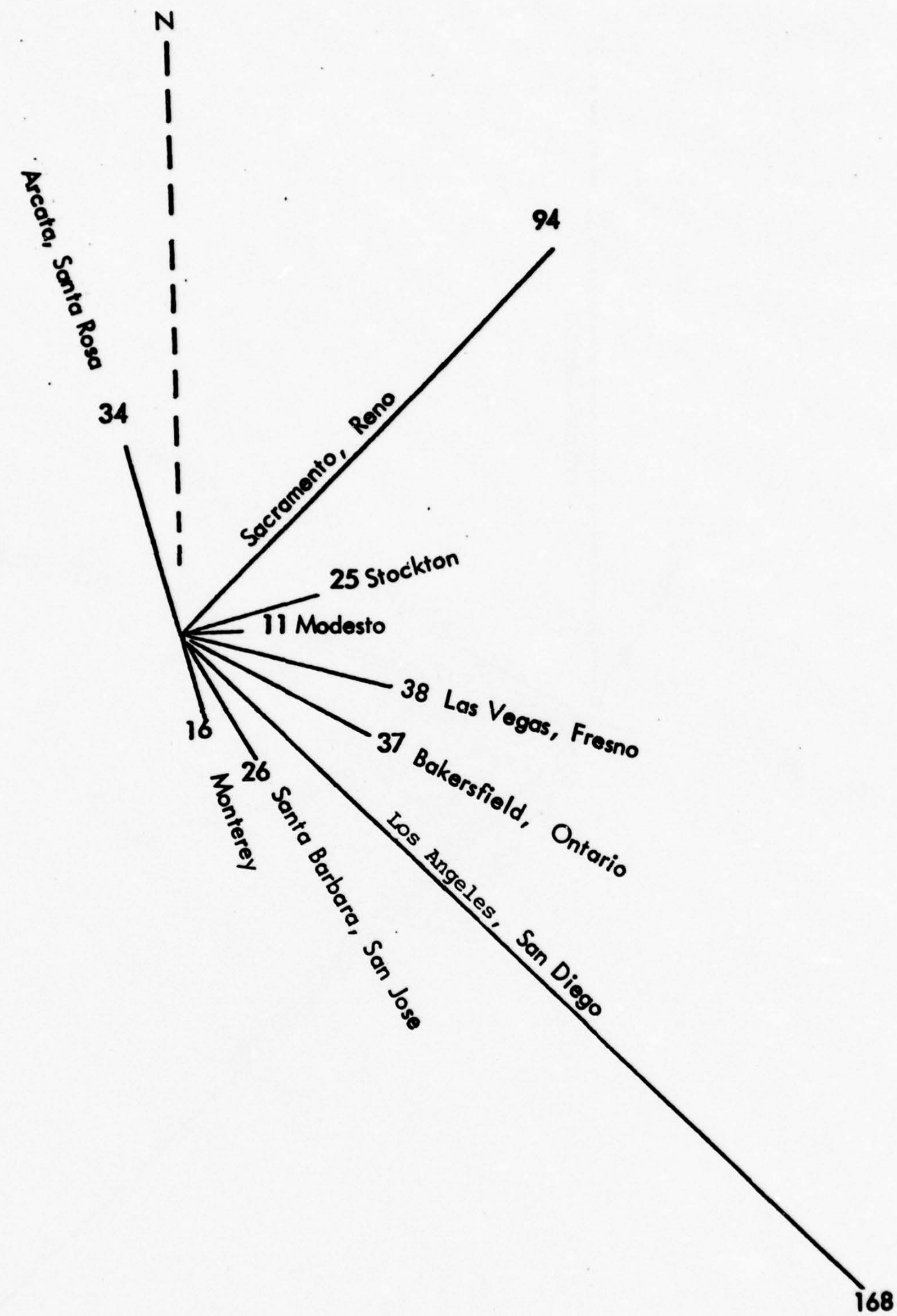


Figure 5.40 San Francisco Low Altitude Traffic Distribution Diagram

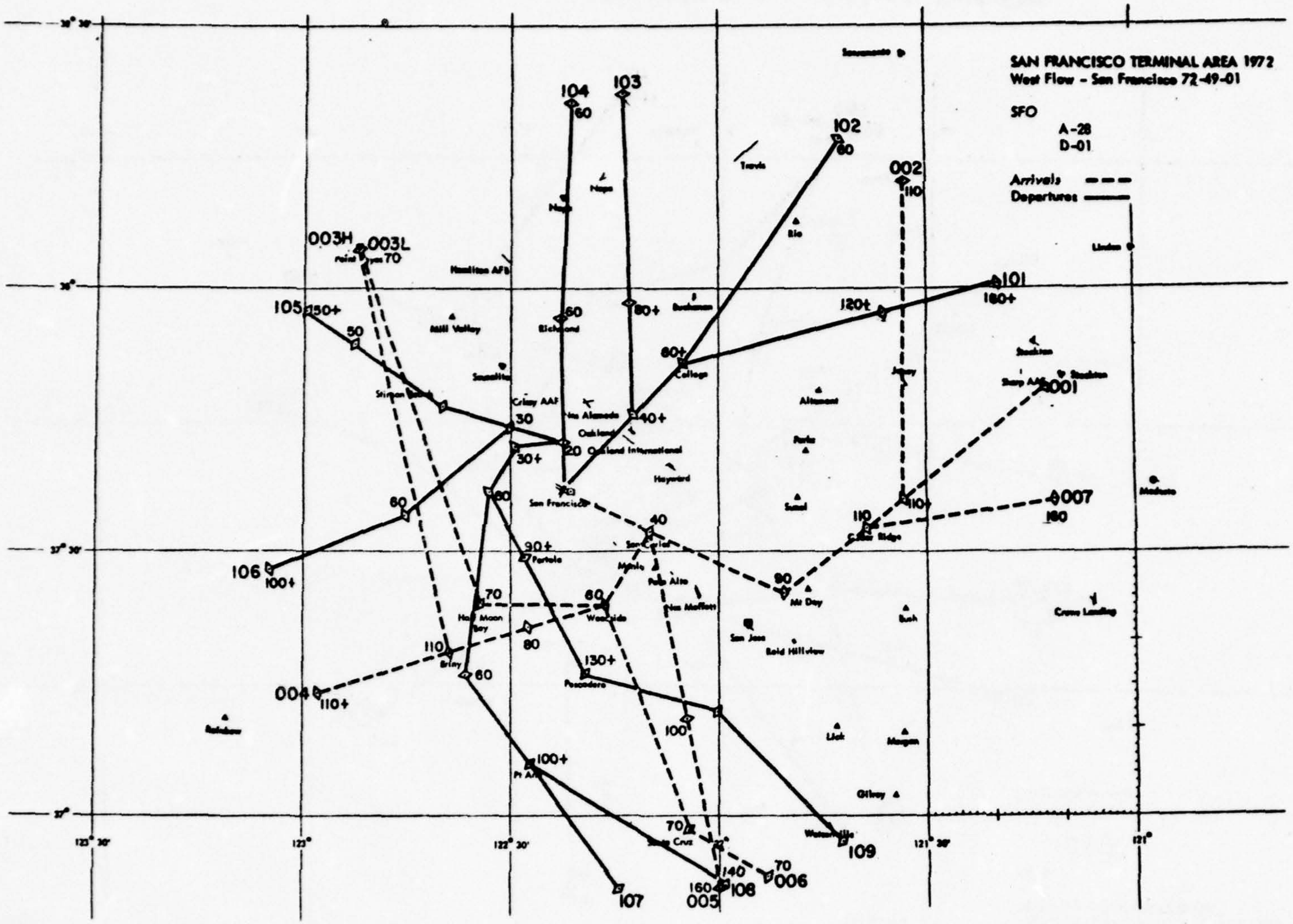


Figure 5.41 San Francisco Terminal Area-1972 RNAV Routes, San Francisco, West Flow

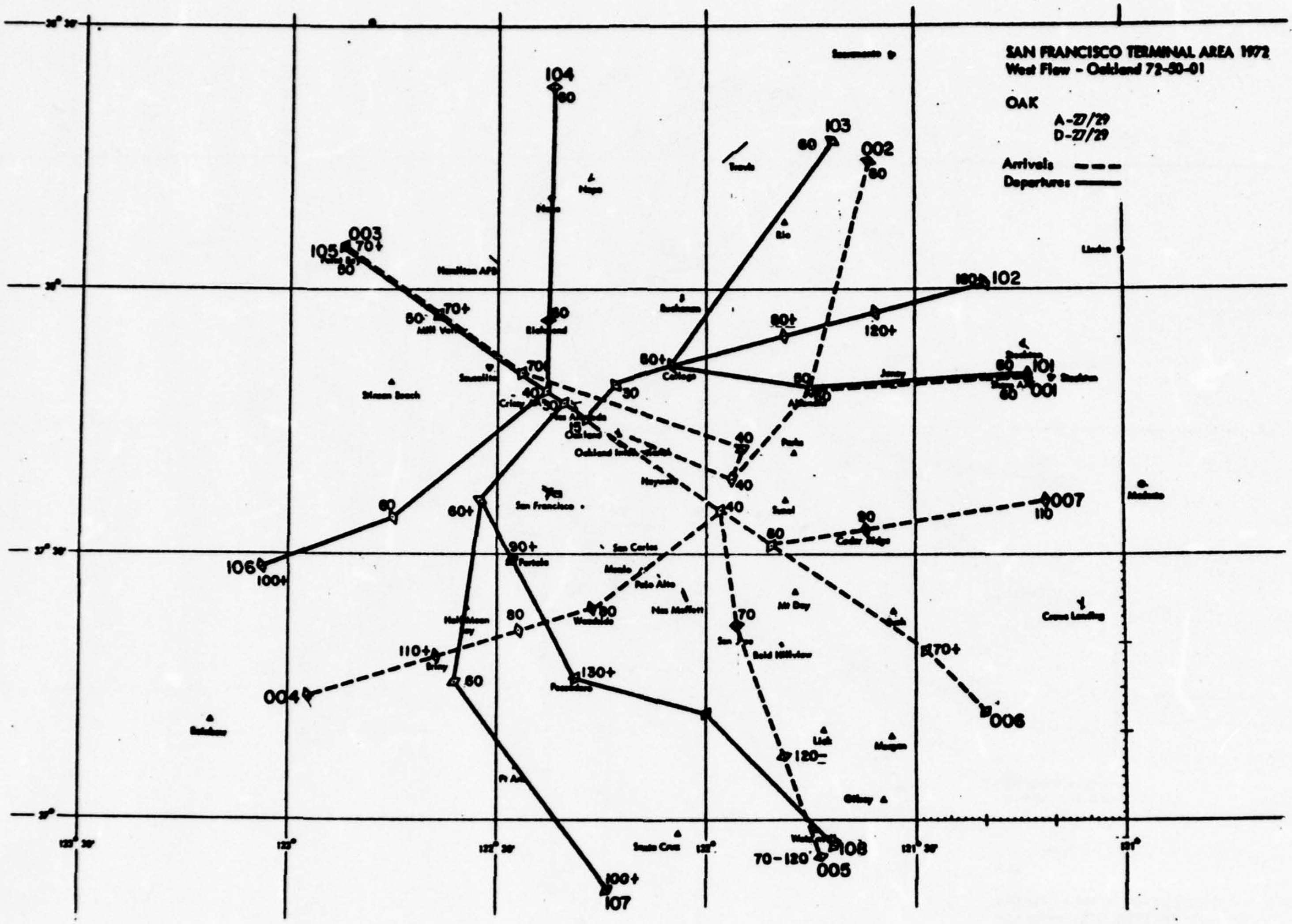


Figure 5.42 San Francisco Terminal Area-1972 RNAV Routes, Oakland, West Flow

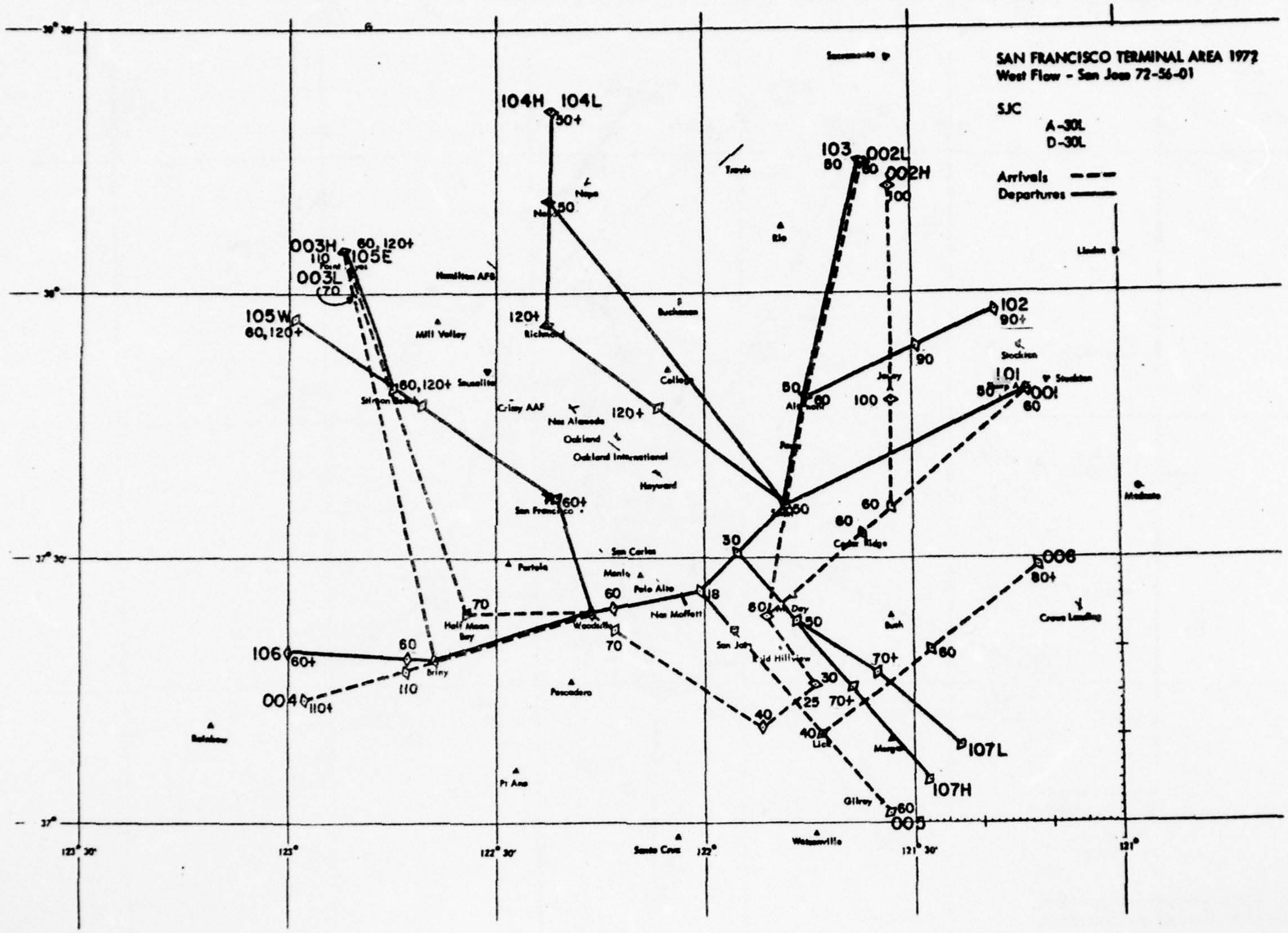


Figure 5.43 San Francisco Terminal Area-1972 RNAV Routes, San Jose, West Flow

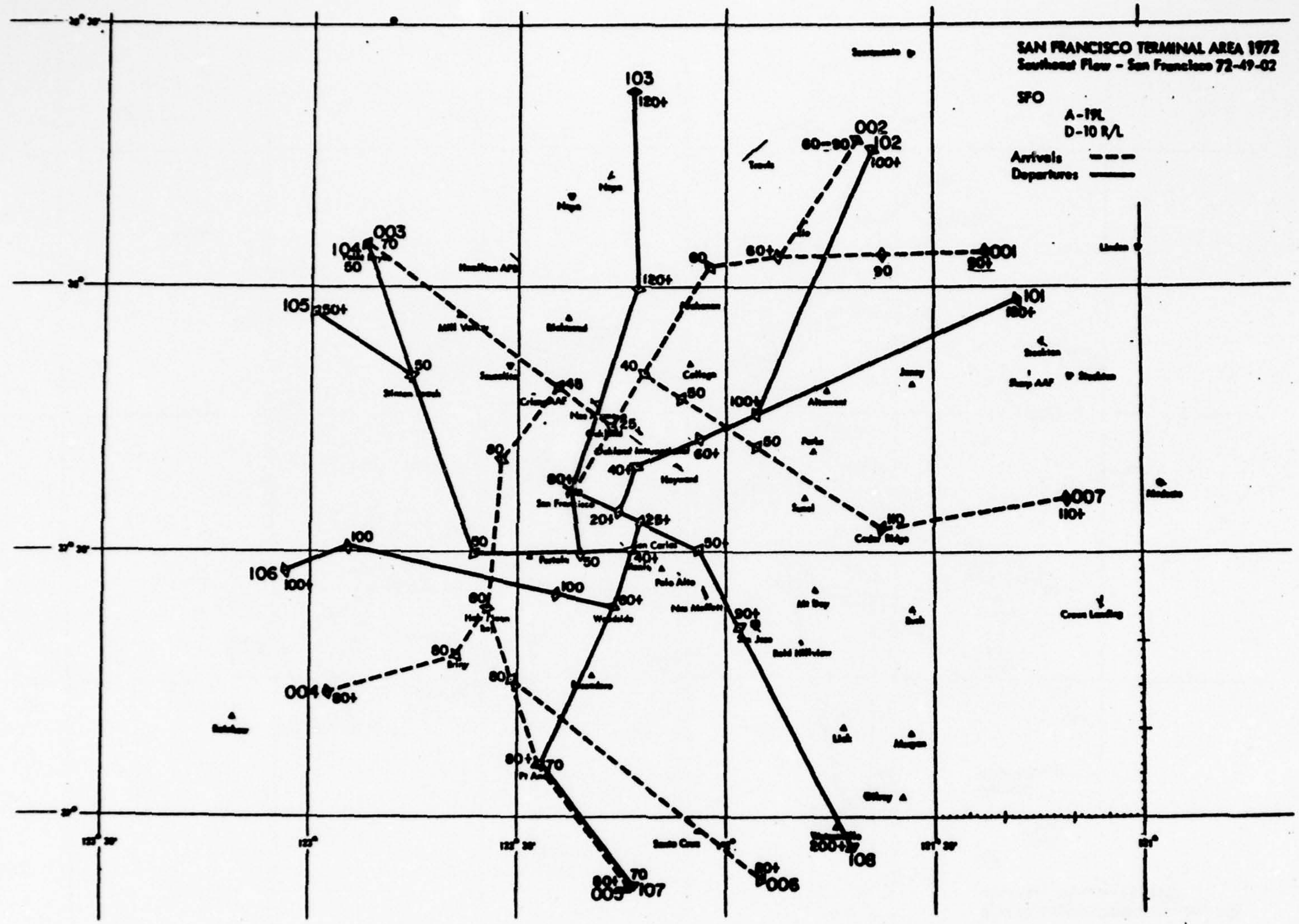


Figure 5.44 San Francisco Terminal Area-1972 RNAV Routes, San Francisco, Southeast Flow

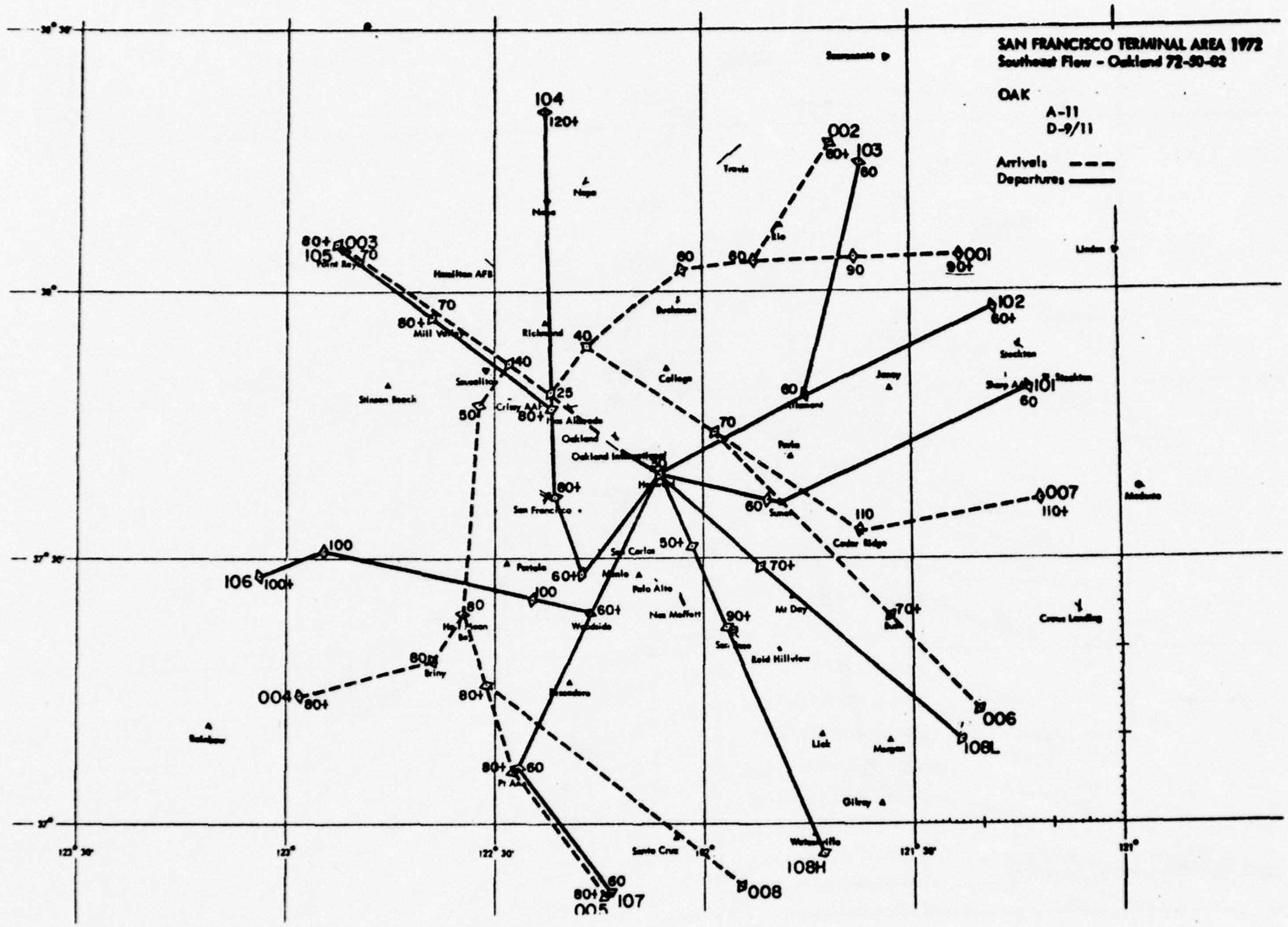


Figure 5.45 San Francisco Terminal Area-1972 RNAV Routes, Oakland, Southeast Flow

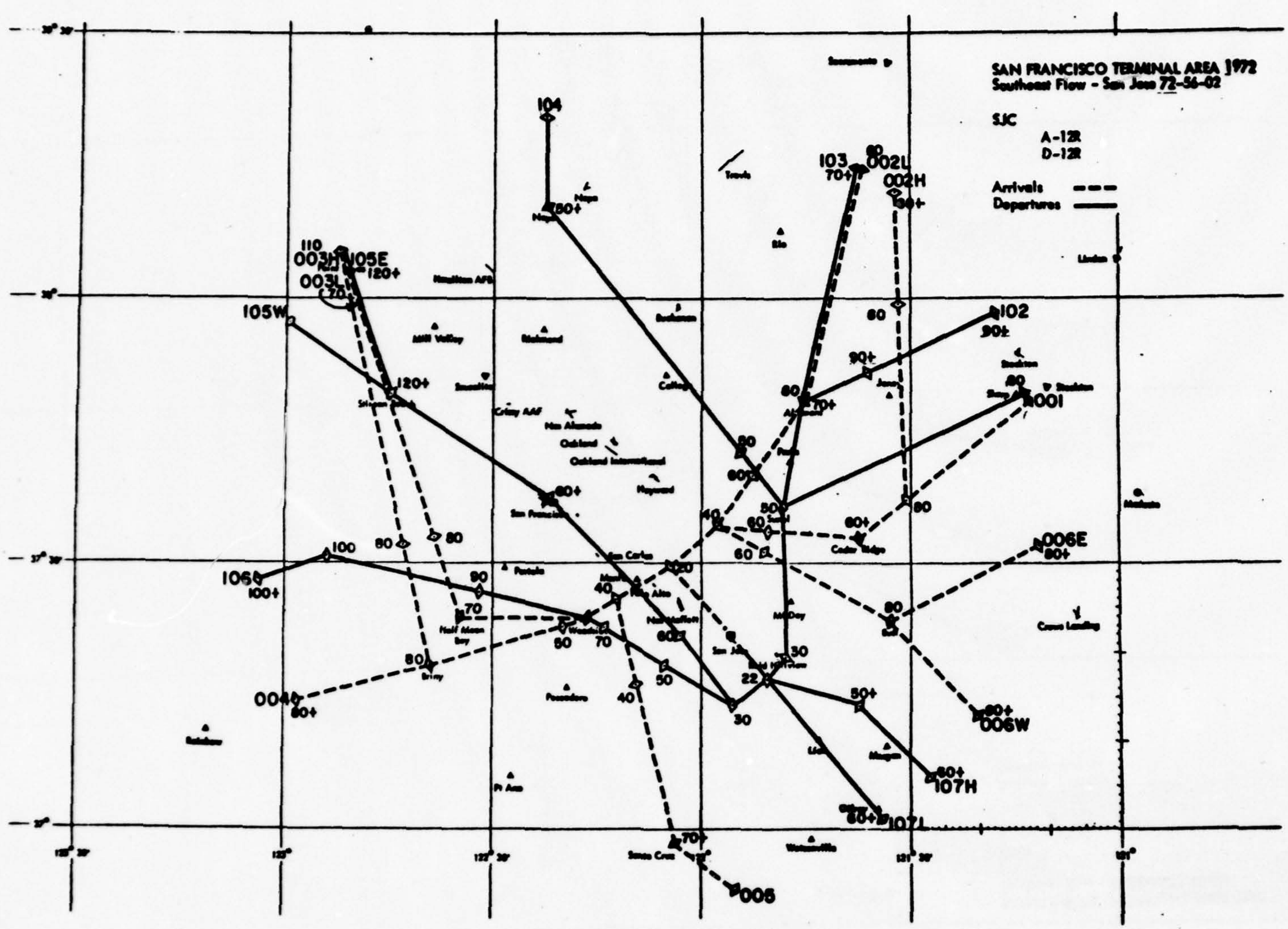


Figure 5.46 San Francisco Terminal Area-1972 RNAV Routes, San Jose, Southeast Flow

can be seen that these traffic patterns do not generally correspond with the octant concept. These routes do, however, correspond with SIDs and STARs in current Bay area operations. These two designs are marked by a concentration of traffic for all three airports over fixes at such places as Cedar Ridge, Sunol, Briny, Point Reyes and Woodside. This concentration often leads to altitude and speed restrictions.

The locations of the three airports at San Francisco are such that a considerable number of altitude restrictions are necessary in order to provide independent routes for all three airports. Even though San Jose is located nearly thirty miles from both San Francisco and Oakland, a considerable number of altitude restrictions and crossing route situations are encountered in establishing route structures for these airports. One reason is due to the fact that the runway extensions for San Jose and the other two airports cross in the vicinity where the intermediate approach fix of one airport and the departure fix of the other airport would ordinarily be located. Consequently runway orientation is one major cause of traffic flow problems at San Francisco.

The primary high altitude arrival routes into the San Francisco and Oakland airports are routes 005 from the south, 007 from the east, 004 from the west and 003H from the north. Routes 003 and 005 (Figures 5.41, 5.42, 5.45) are also the arrival routes for San Jose from the north and south while route 006 carries the eastern arrivals (Figures 5.43 and 5.46). The high altitude departure routes for San Francisco are routes 109 to the south and southeast, route 101 to the east, route 104 to the north and route 106 to the west (Figures 5.41 and 5.44). The Oakland departure routes for high altitude jet traffic are 108 to the south and southeast, 102 to the east, 104 to the north and 106 to the west. (Figures 5.42 and 5.45). San Jose departures for high altitude traffic are made on routes 107H to the south, 102 to the east and 104H to the north.

The low altitude traffic patterns in the San Francisco area are greatly influenced by the active runways and the particular airport within the San Francisco area which is being used as the origin or destination airport. The concept of common low altitude arrival fixes for high and low altitude aircraft that was used in the traffic patterns at New Orleans, Denver, Philadelphia and Miami is not used at San Francisco. Instead, separate routes are given to the low altitude traffic so that departures may proceed to their destination airport and arrivals may enter the terminal area in a manner which provides them a shorter routing than would be obtained if they were constrained to follow the high altitude routes.

The San Francisco area is a very good example of the impact that multiple major airports may have upon terminal area traffic patterns. For instance in the West Flow configuration in Figure 5.41 the area in the vicinity of Hayward Airport would usually be used for a base leg entry to Runway 28L at SFO. However, this area is needed for the final approach maneuvering area for OAK. Similarily in Figure 5.42 the area over San Carlos Airport is required for the SFO final approach rather than the downwind and base leg for OAK. Thus it is apparent that metroplex areas like the San Francisco area will impose constraints upon terminal area route structures that are not found in the single major airport terminal areas such as those that were analyzed in Sections 5.1.1 through 5.1.4.

5.1.5.3 The 1972 Task Force Concept at San Francisco

Due to the three major airports at San Francisco and their relative runway orientation, the San Francisco area is considerably more complex from a terminal route standpoint than the terminals at New Orleans, Denver, Philadelphia and Miami. The major effect of this complexity occurs in the necessity to locate routes in non-optimum locations and to impose altitude restrictions on routes to the various airports in order to provide independent arrival and departure routes.

The routes in the present radar vector/VOR environment at San Francisco generally are designed to serve the enroute traffic flow. These routes do not lie within the Task Force terminal area octant concept however. Because the present traffic flow generally served the terminal users in a reasonably direct manner and because the introduction of independent RNAV routes at San Francisco could cause additional altitude restrictions on some routes, no new independent RNAV routes were developed for this 1972-1977 time period.

Traffic in the terminal maneuvering area also does not follow the recommended Task Force traffic concept. The traffic to each airport often utilizes only a single traffic pattern on one side of the airport or the other but generally not both. To use both sides of the airport would create several more altitude restrictions.

No difficulty was encountered in developing RNAV routes which generally overlie the vector routes. RNAV routes to all three major airports were developed for routes from the airport to the enroute connecting points and vice versa.

5.1.5.4 The Amended 1972 San Francisco Terminal Area Design

No major changes were made to the terminal area route structure for the West Flow at San Francisco (Figure 5.47). The major difference between the routes depicted in Figures 5.41 and 5.47 is the deletion of the propeller aircraft routes in Figure 5.47. At San Francisco there are a number of areas in which the propeller aircraft routes are different from the jet aircraft routes. In the initial design task both of these route structures were shown. However, the user benefits analysis that was performed subsequent to the development of the 1972-77 and post-1982 RNAV route structures made use of turbine powered aircraft exclusively. Consequently, in the amended 1972-77 designs, the propeller routes were deleted. It should be noted, however, that the omission of these routes should not be construed to mean that RNAV routes in the terminal area cannot be developed for propeller aircraft. Also, some slight adjustments were made to the waypoint altitudes. However, in general, the route structure for the west flow remained intact.

In the amended 1972 southeast flow route structure for San Francisco, Figure 5.48, there are a number of changes from those routes depicted in Figure 5.44. The propeller aircraft routes were deleted in this design as well. In addition, several routes were moved both in the terminal maneuvering

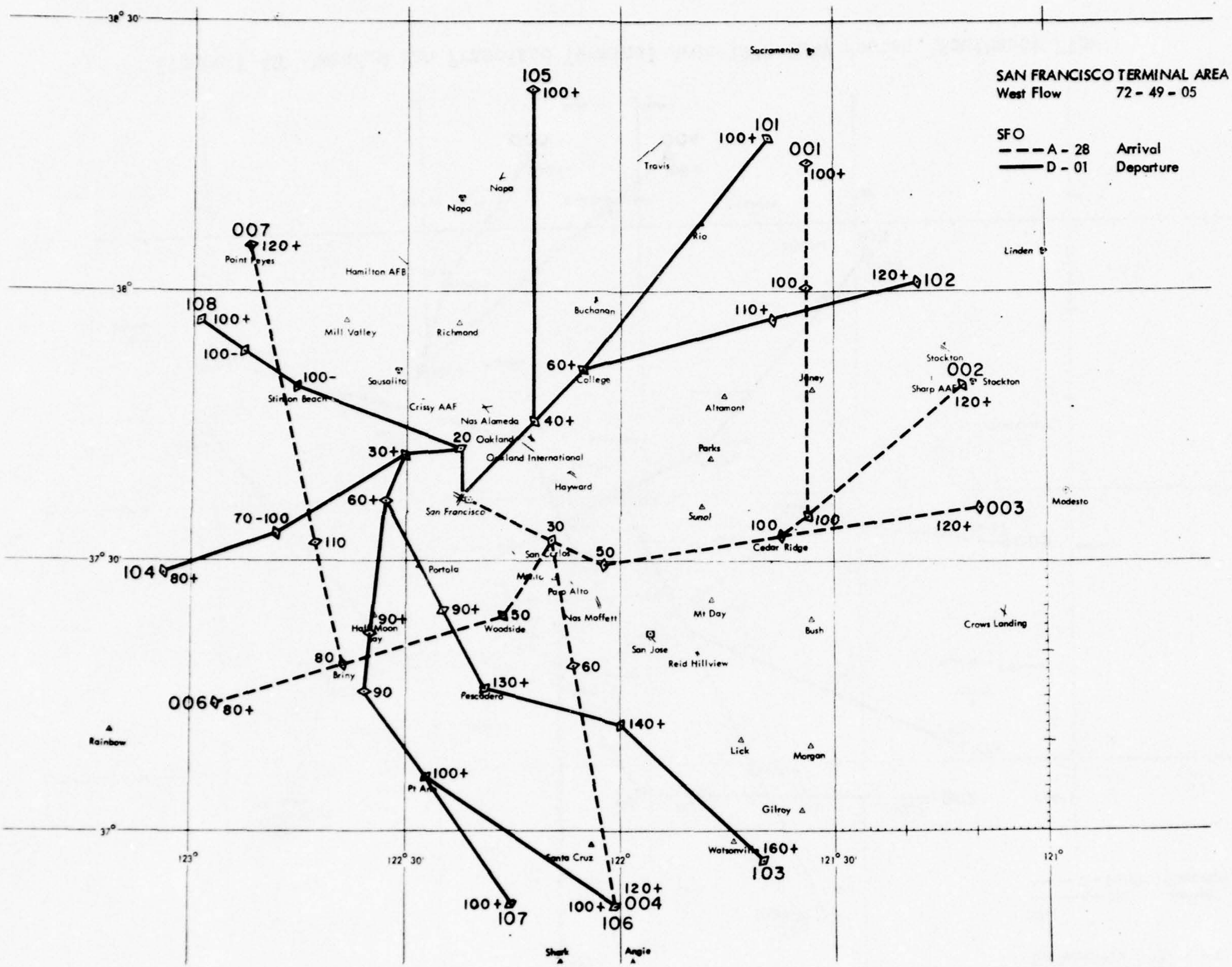


Figure 5.47 Amended San Francisco Terminal Area-1972 RNAV Routes, West Flow

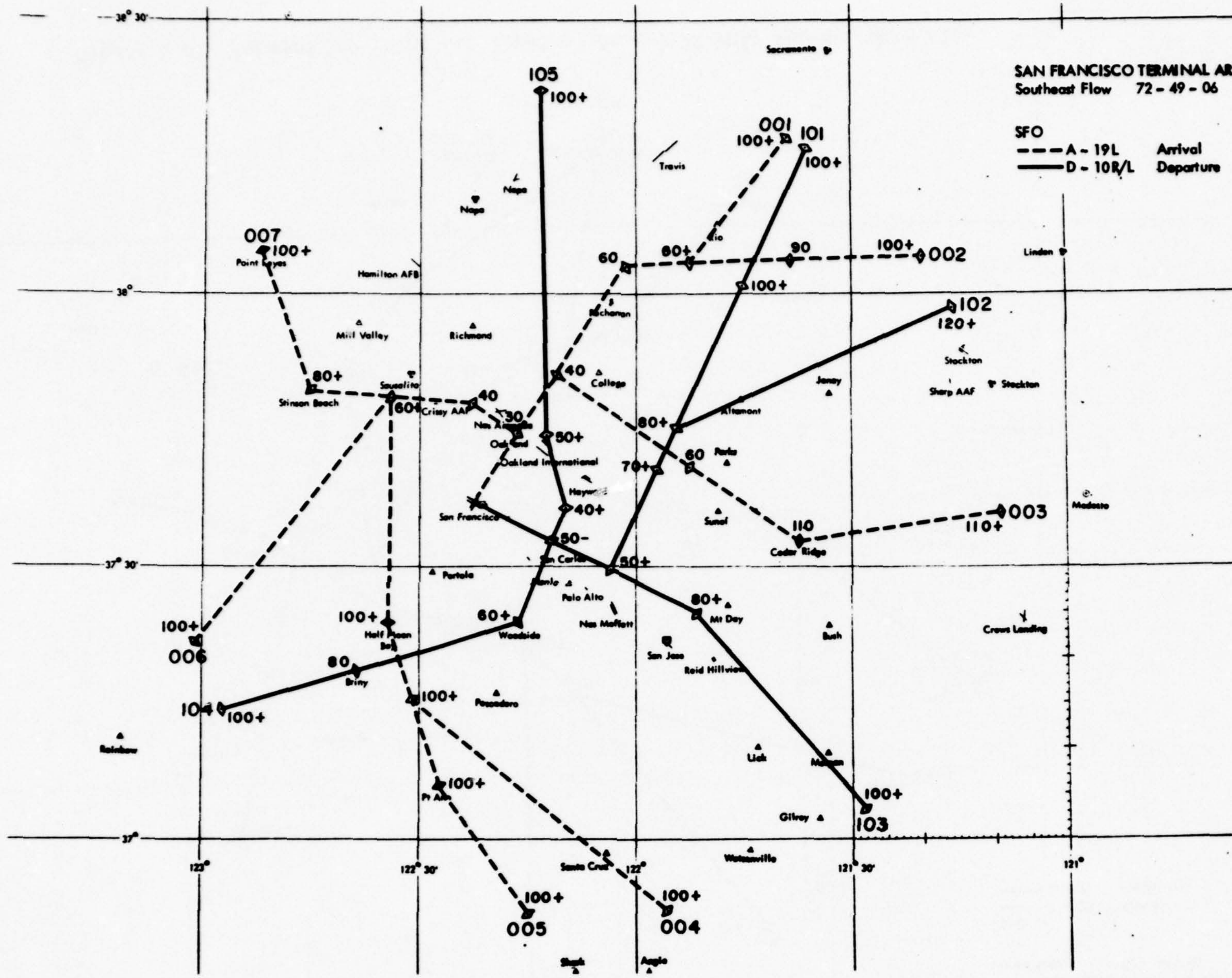


Figure 5.48 Amended San Francisco Terminal Area-1972 RNAV Routes, Southeast Flow

area and at the terminal enroute boundary point. For example, departure route 103 was moved approximately 5 miles northeast. Aircraft using this route proceed to the southeast to Avenal VORTAC which is south of the area on the map. The oceanic routes southwest of the airport are modified also. In the west flow configuration arrivals are kept south of departures. In the southeast flow configuration the opposite is true. This provides a more direct route to the airport for both arrival and departure traffic. Arrival route 007 was modified slightly as well. In the previous design the route was shown to follow a long base leg entry to the terminal maneuvering area from Point Reyes VORTAC to the intermediate approach waypoint which is located about 7 miles from the airport along the final approach path. The San Francisco controllers suggested that the usual practice is to bring the aircraft south of Point Reyes to near Stinson Beach whereupon a modified downwind leg entry is made to the terminal maneuvering area. The final major change in the southeast flow route structure concerns route 105. In the original design, aircraft departing the terminal area to the north were shown as making a 240° climbing right turn and proceeding back over the airport and then intercept a north bound Oakland VORTAC radial. In the amended design the aircraft makes a 120° left turn whereupon they intersect the same Oakland radial.

5.1.6 Chicago

5.1.6.1 Characteristics of the Chicago Terminal Area

Airport Configuration

The Chicago terminal area is composed of one major airport, O'Hare International, one major satellite, Midway, and several minor satellite civil and military airfields. O'Hare is the world's busiest airport and consequently must be considered the dominant element in any Chicago airspace design. Traffic activity data from the peak day IFR tape are presented in Table 5.2 for O'Hare, Midway and several satellite Chicago area airports.

TABLE 5.2 DAILY INSTRUMENT OPERATIONS

AIRPORT	IDENTIFIER	NUMBER OF OPERATIONS	%LOW ALTITUDE FLIGHTS
O'Hare International	ORD	1818	25%
Midway	MDW	294	49%
Pal-Waukee	PWK	67	74%
Glenview NAS	NBU	23	70%
Sky Harbor	OBK	7	100%

Based on this distribution of traffic at each of the airports, the design for each time period was based upon providing efficient traffic flow patterns for O'Hare with some considerations given to the Midway traffic. Traffic to the remaining satellites was not considered sufficient to influence the design for any time period.

Runway Orientation and Utilization

The runway patterns for O'Hare and Midway are shown in Figures 5.49 and 5.50. It is apparent that both airports have complex runway configurations. The large number of runways and the relative orientation with each other permit the use of many runway configurations at ORD. Some of the combinations are presented below:

	LAND	DEPART
1.	(14R & 14L)	(09L & 27L) or 09L & 09R) or (09L & 14R)
2.	(14R, 14L & 09R)	(09L, 14R & 09R) or (04R & 04L)
3.	(09R & 09L)	(14R & 14L) or (04R & 04L)
4.	(09L & 04R)	(04L & 09R)
5.	(04R & 04L)	(09R & 09L) or (04R & 04L)
6.	(32R & 32L)	(32R & 27L)
7.	(27R & 32L)	(32R & 27L)
8.	(27R & 27L)	(32R & 32L)
9.	(22R & 27L)	(27R, 27L & 22L)
10.	(22R & 22L)	(27R & 27L)
11.	(14R & 22L)	(09R & 09L)
12.	(14R & 22R)	(09R & 09L)

Of seven runway pairs at O'Hare, the four pairs that are most used are the following:

09L - 27R
09R - 27L
14L - 32R
14R - 32L

The 4L - 22R and 4R - 22L runways are more noise sensitive and shorter than the preferred runways. The 18-36 runway is too short for most of the air carrier traffic using ORD. Based upon the information provided by the Chicago Terminal Facility through the data collected by NAFEC and by direct observation of the Chicago Terminal operations, the following configurations for O'Hare were considered representative and were chosen for analysis:

	Land	Depart
Configuration 1 (Southeast Flow)	14R, 14L	14R, 09L, 09R
Configuration 2 (West Flow)	27L, 27R	27L, 32R, 32L

Compatible flows were selected for Midway by selecting the following MDW runways:

	Land	Depart
Configuration 1	13R	13R, 13L
Configuration 2	31L	31L, 31R

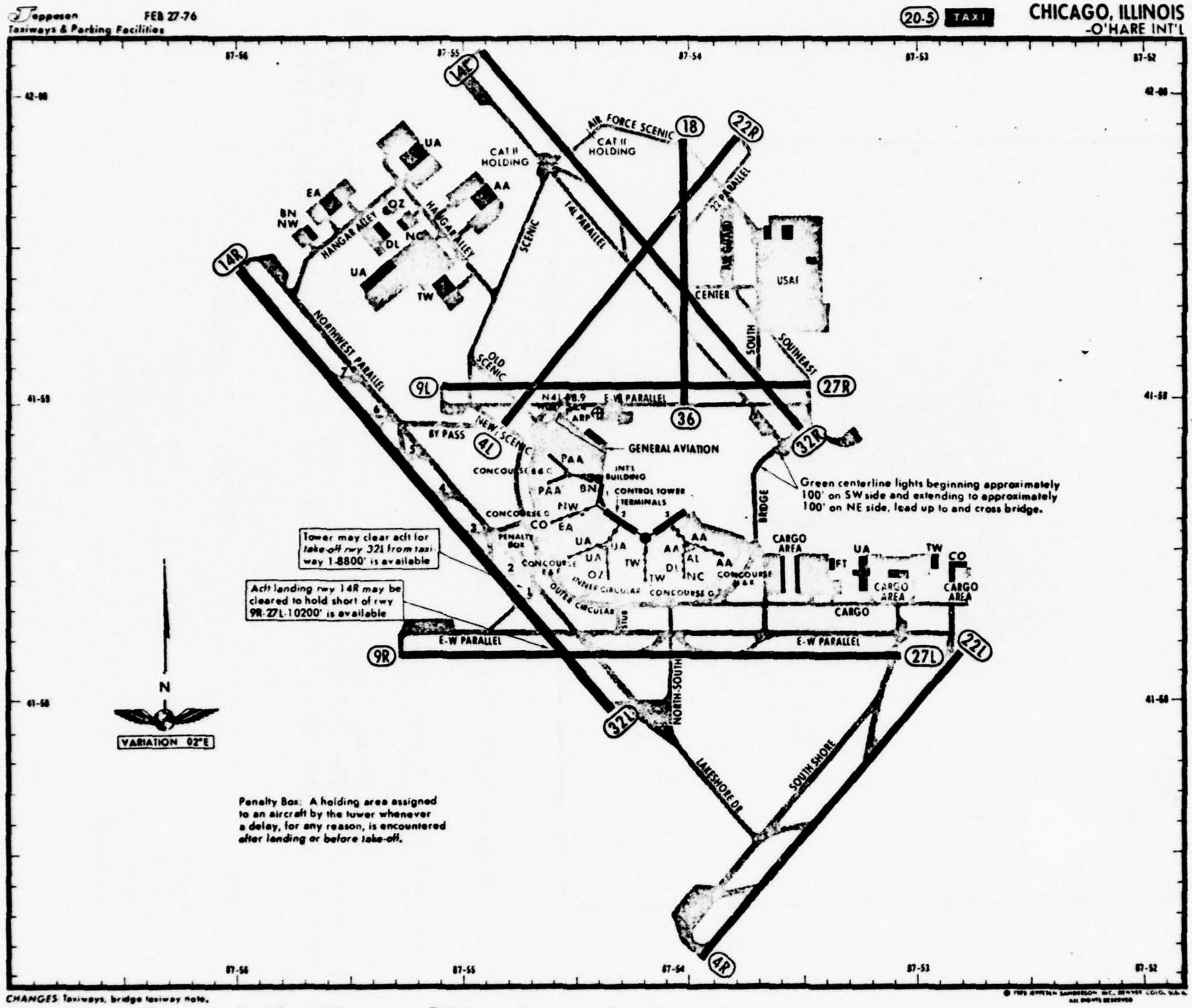


Figure 5.49 Chicago O'Hare Airport Configuration

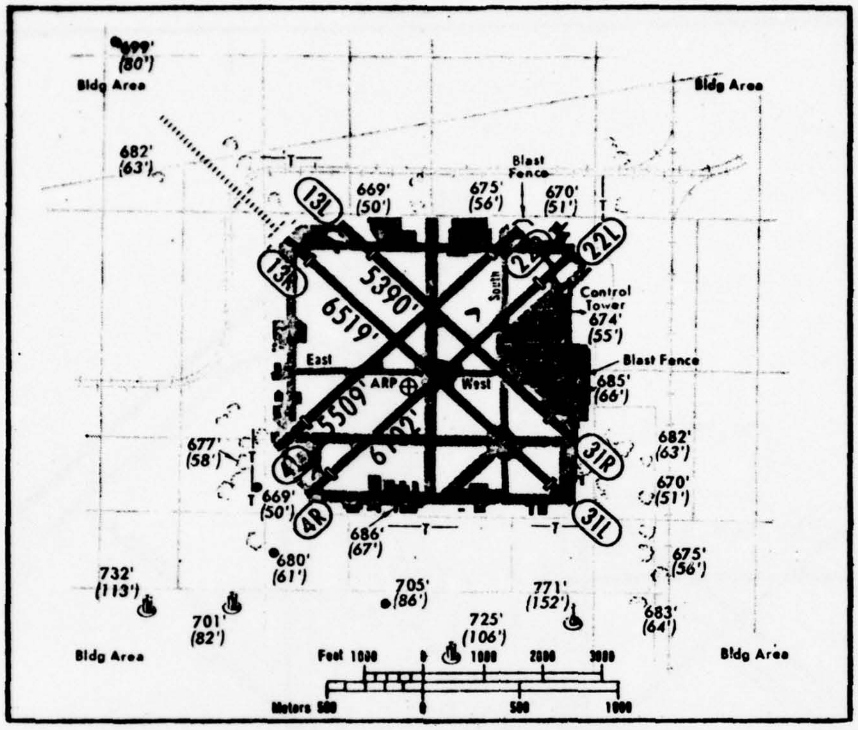


Figure 5.50 Chicago Midway Airport Configuration

Terminal Area Traffic Flow

The present Chicago terminal area traffic flow is pictured in Figure 5.51 and is compared to the Task Force octant concept. Arriving traffic for ORD comes over one of four feeder fixes. They are in order of estimated traffic density:

Fix	Direction of Arrival
Plant	Southeast
Warren	Southwest
Papi	Northeast
Lakewood	Northwest

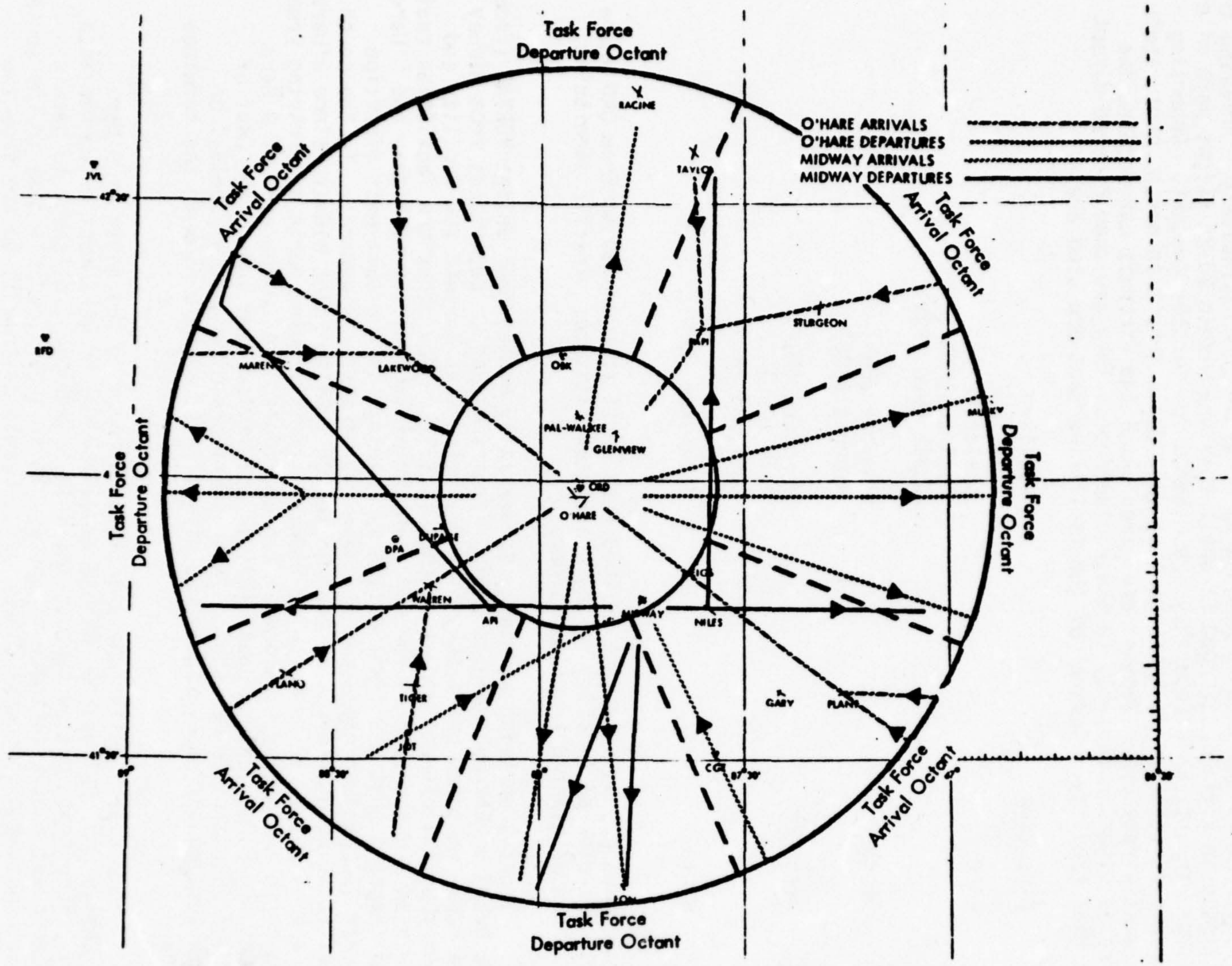


Figure 5.51 Current Chicago Traffic Flow vs. the Task Force Octant Concept

Traffic generally converges from two or three Victor airways to each of these fixes. Navigation is accomplished by radar vectors exclusively. Arriving traffic is assigned an altitude of 7000 ft until they are within 20-25 flight path miles of the airport, whereupon they are cleared for further descent. Departing traffic is vectored on headings that send the aircraft in north, east, south or west directions. Vectors are given until the aircraft can receive the first navigation facility in their clearance. They are then cleared direct to that facility. Several of the facilities that are used are:

Direction	Facility
East	Keeler(ELX) Pullmann(PMM) South Bend (SBN)
South	Peotone (EON) Roberts (RBS)
West	Bradford (BDF) Polo (PLL) Rockford (RFD)
North	Milwaukee (MIU)

Departures are usually kept at 5000 feet until they are 30 nm from ORD where they are cleared to climb to their assigned altitude. Traffic permitting, they can be cleared to climb sooner.

Traffic arriving at Midway is generally routed over Joliet VORTAC (from the West) or Chicago Heights VORTAC (from the East). Departures from Midway are radar vectored until they pick up their first enroute VOR facility and then they are cleared direct to that facility. The departure facilities that are used are the same as for ORD. The relative position of Midway and O'Hare, and the fact that the traffic flow is heaviest in the east-west direction, permit independent operation of these two airports in general. To the south, traffic using O'Hare can be kept on top of traffic using Midway, since O'Hare is approximately 12 nm north of Midway. Traffic going north or arriving from the north for Midway uses one of two corridors, one to the east of O'Hare along the Lake Michigan coast (Niles-Papi-Taylor) and one to the west of O'Hare (Napierville-Marengo). These corridors alternate as arrival or departure routes depending on the direction of traffic flow in the terminal area.

Some traffic using the satellite airports to the north of O'Hare (Glenview NAS, Pal-Waukee, Chicagoland, and Sky Harbor) must be worked into the O'Hare traffic flow because there is insufficient airspace to permit independent routes to these airports. This is particularly true in the southeast, south and southwest directions. Satellite traffic to and from the northweast, north and northwest can use the Northbrook VORTAC (OBK) and remain independent of O'Hare traffic.

As was mentioned in a previous section, several runways are used at O'Hare,which presents an opportunity for a degree of flexibility in alignment of the octant pattern of the standard terminal area design. Since the two principal sets of parallel runways (09-27 and 14-32) intersect at an oblique angle, their respective octant patterns cannot coincide. It can be seen from Figure 5.51 that the octant pattern based upon the 09-27 runways and the current flow patterns for Chicago are in almost perfect alignment. Consequently, this pattern was chosen as the basis for the design. The only cross-grain flow that can be observed arises from the area south of O'Hare. Since most north departures and south arrivals are Milwaukee traffic, they are handled by tower enroute procedures and they are assigned altitudes below 7,000 ft. Consequently, this cross-grain pattern does not greatly affect other O'Hare and Midway traffic. In a similar manner the Midway traffic can fly beneath the O'Hare traffic until the arrivals and departures can be established in the proper octant. As a result, neither of these cross-grain flows need affect the octant pattern traffic flow.

Control Jurisdiction

The fully staffed TRACON positions are presented in Table 5.3. Their precise area of responsiblility varies from configuration to configuration and with the level of TRACON staffing. During off peak traffic periods positions are often combined.

TABLE 5.3 CHICAGO TRACON POSITIONS

FUNCTION	NUMBER OF POSITIONS
Arrival Control	2
Departure Control	3
Arrival Data	2
Departure Data	2
North Satellite Control	1
South Satellite Control	2
South Satellite Data	1
Monitor	2
Supervisor	1
Runway Use Clerk	1

The numerous runways at O'Hare permit an extremely flexible type of operation at the Chicago TRACON. To utilize this flexibility a high degree of coordination has been developed at Chicago. Each controller is required to be able to operate each control position so that he is familar with the operation and responsibilities of each position in the TRACON. In this way a high degree of coordination is possible.

Enroute Connecting Points

Traffic distribution diagrams for cities which exchanged 10 or more flights per day with Chicago computed from 1971 IFR peak day records are shown in Figures 5.52 and 5.53. It is quite evident from the low altitude traffic distribution diagram that low altitude Chicago traffic is quite uniformly distributed

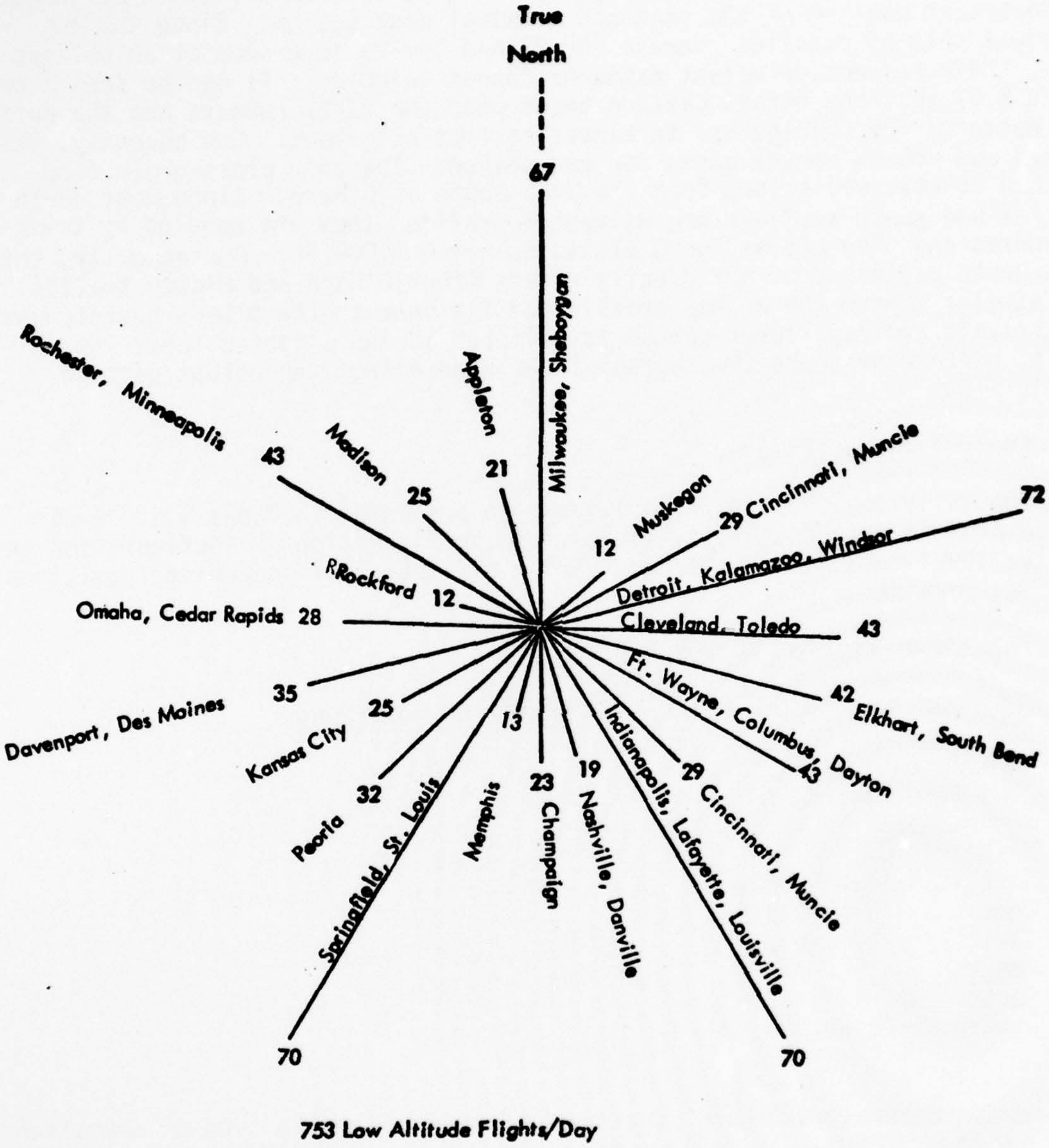


Figure 5.52 Chicago Terminal Area Low Altitude Traffic Distribution Diagram

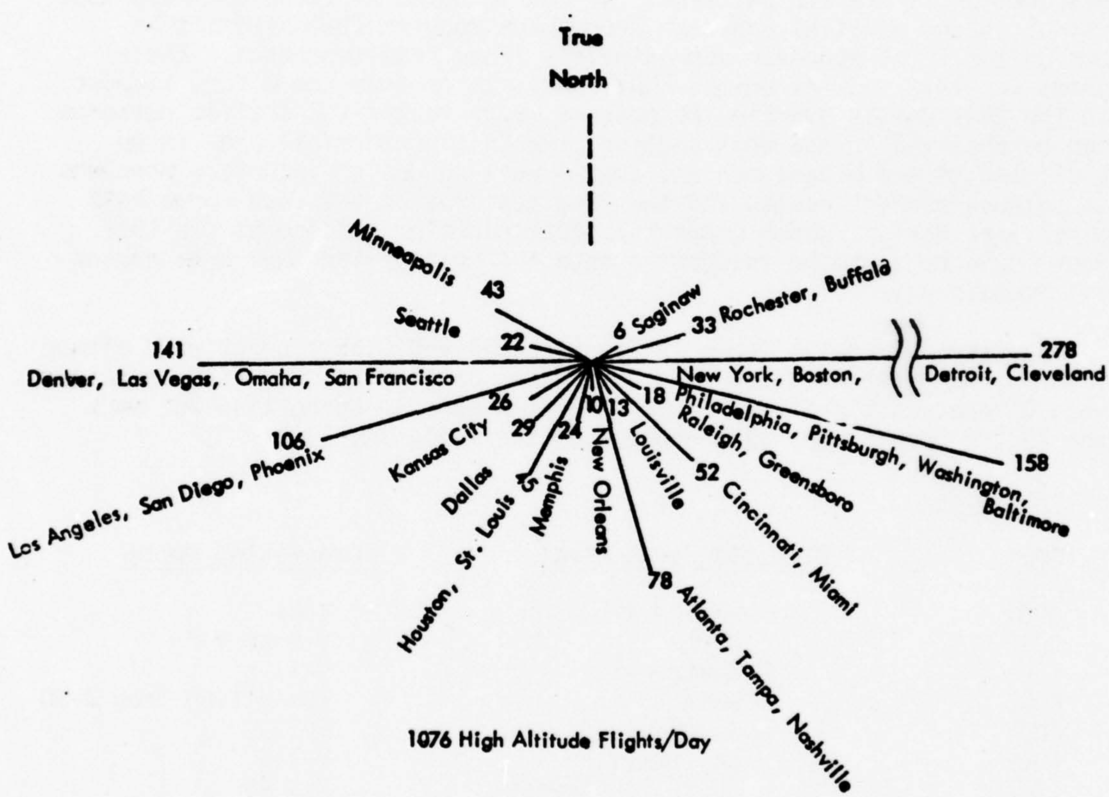


Figure 5.53 Chicago Terminal Area High Altitude Traffic Distribution Diagram

in all directions. Consequently arrival and departure routes must be provided for low altitude traffic in all directions from Chicago. The high altitude traffic distribution reflects the high density of east-west flights into and out of Chicago and a moderate southerly flow of traffic. There is almost no high altitude traffic to the north.

5.1.6.2 The 1972 Chicago Terminal Area Design

Figures 5.54 and 5.55 depict the arrival and departure routes that are in current use at Chicago O'Hare. Figure 5.54 represents southeast flow (Configuration 1) traffic patterns and Figure 5.55 shows west flow (Configuration 2) traffic patterns. It can be noted on these diagrams that the simultaneous parallel approach procedures require that aircraft be turned on the final approach approximately 17 nm from touchdown. These diagrams for 1972 show no unique RNAV routes to or from the O'Hare airport since the RNAV routes overlie the present radar vector-VOR traffic patterns. As can be observed in the next section, the Chicago terminal area is so well aligned to the octant concept that almost no design interface problems exist between current routes and the flow patterns of the Task Force RNAV terminal area design, which means that from a design standpoint the 1977 designs could begin to be integrated into the Chicago terminal area routes almost immediately.

The terminal routes shown in Figures 5.54 and 5.55 connect with either a Victor airway, a transition to a Jet route, or with a tower enroute pattern between O'Hare and the Milwaukee TRACON. The enroute connection for each of the 1972 O'Hare routes is presented in the following list:

ARRIVALS

Route	Direction of Arrival	Connecting Route
C001	Northeast	V-84
C002	North	V-9 or V-7
C003	Northwest	V-97
C004	West	Transition from J-30
C005	Southwest	V-10
C006	Southwest	V-116
C007	South, Southwest	V-9-69
C008	South, Southeast	V-7-51-97
C009	Southeast	V-422
C010	East, Southeast	Transition from J-30
C011	East	V-8-92-126

Route C002 has two connecting routes listed because this is a tower enroute radar vector route between O'Hare and Milwaukee and as the traffic patterns at O'Hare change, the terminus for route C002 changes which can be seen by comparing Figure 5.54 and 5.55.

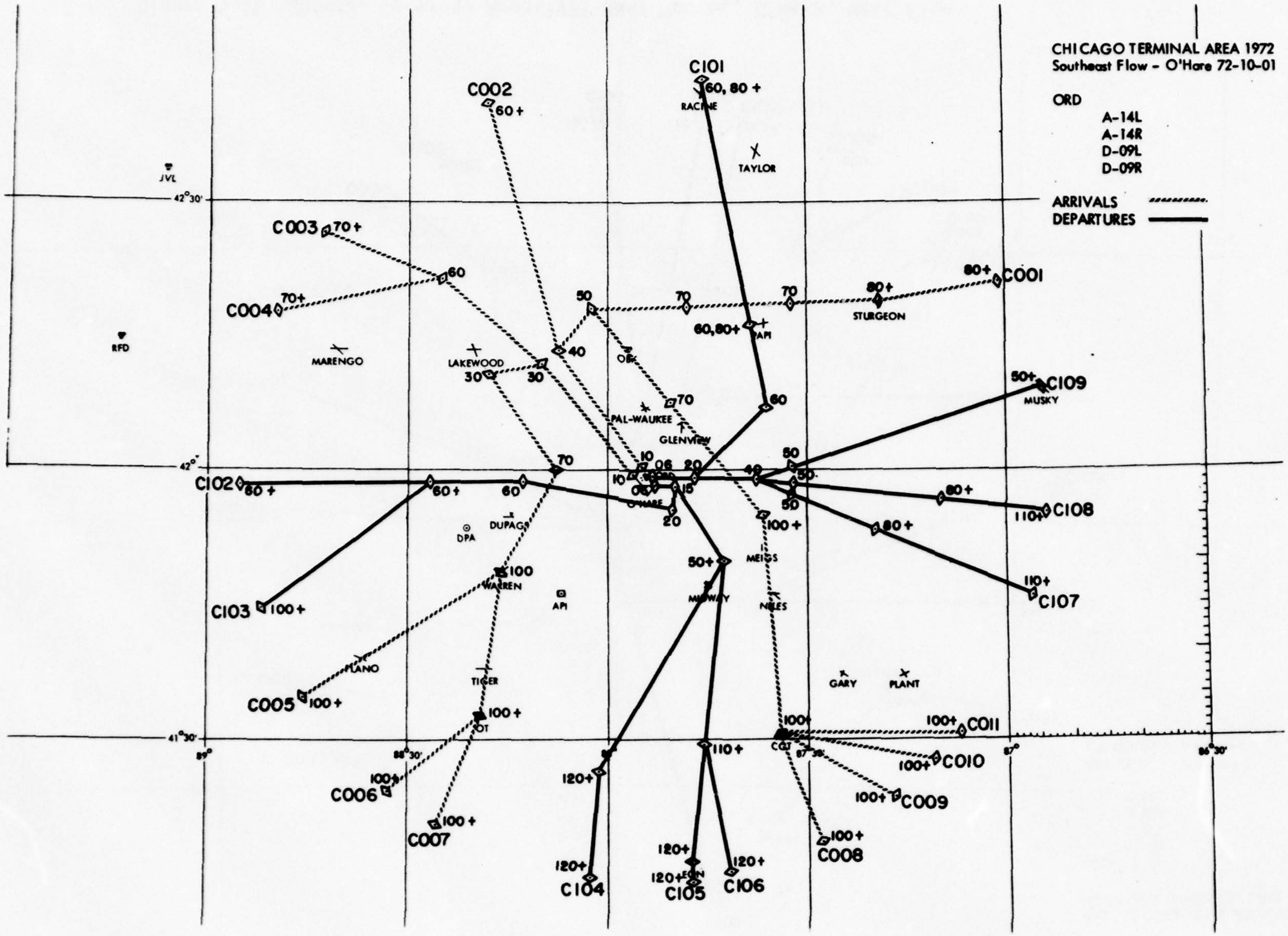


Figure 5.54 Chicago Terminal Area-1972 RNAV Routes, O'Hare, Southeast Flow

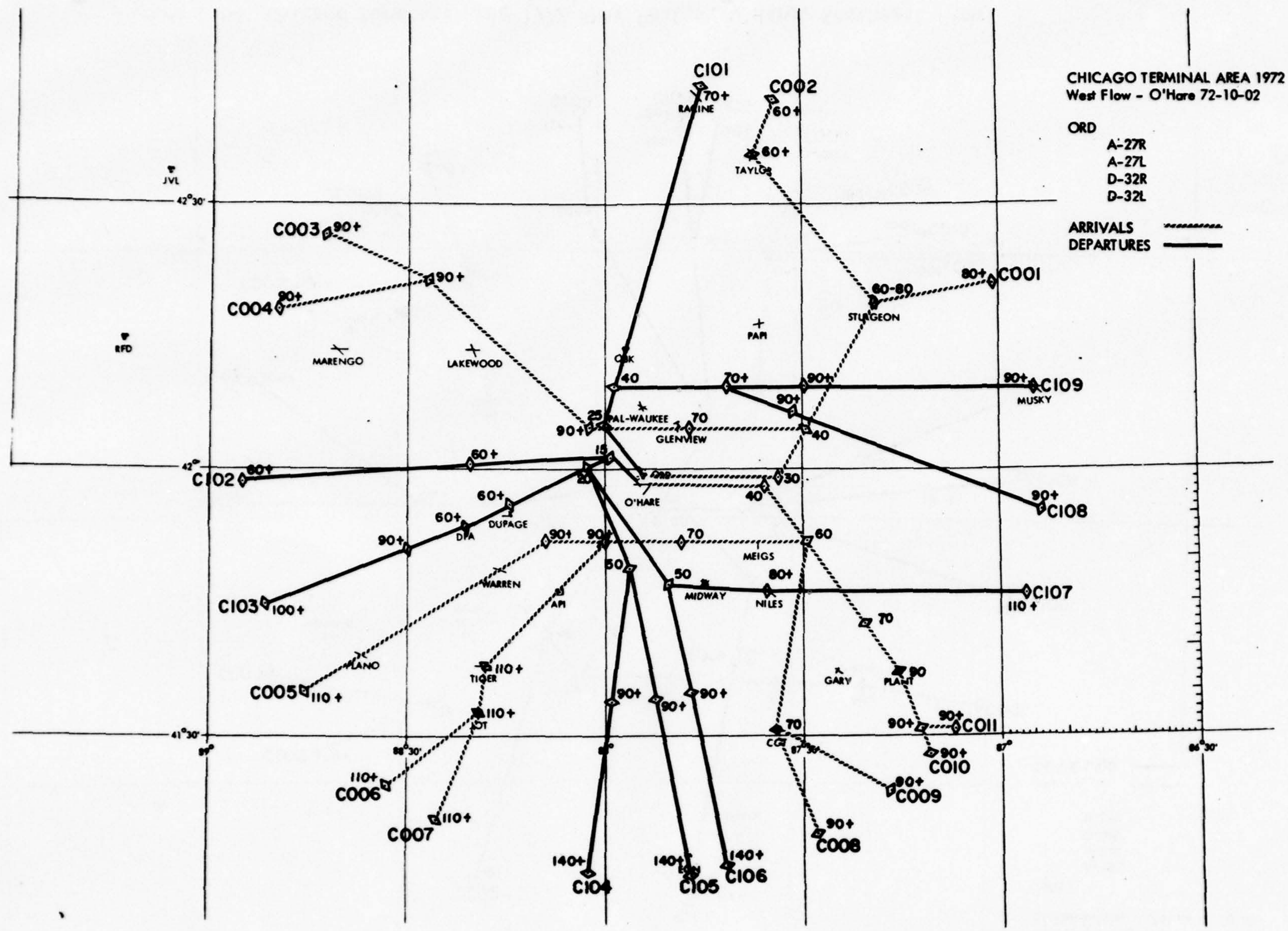


Figure 5.55 Chicago Terminal Area-1972 RNAV Routes, O'Hare, West Flow

DEPARTURES

Route	Direction of Departure	Connecting Route
C101	North	------
C102	West	V-172
C103	Southwest	V-84
C104	South	V173-191
C105	South	V53-128-171
C106	Southeast	J-99
C107	East, Southeast	V-6-10
C108	East	V-172-228
C109	Northeast	V-100-116-218

Route C101 is a tower enroute radar vector route to Milwaukee.

Arrival and departure routes that are currently being used for Chicago Midway are shown in Figures 5.56 and 5.57.

The distribution of arrival and departure routes at Midway is reflected in the high density of routes to the east, west and south and the small number of routes to the north. The current connecting routes for Midway arrivals and departures are listed as follows:

ARRIVALS

Route	Direction of Arrival	Connecting Route
M001	North	V-7 or V-9
M002	Northwest	V-171
M003	West	V-38
M004	Southwest	V-116
M005	South, Southwest	V-9
M006	South, Southeast	V-7-51-97
M007	Southeast	V-422
M008	East	V-8-92-126

DEPARTURES

Route	Direction of Departure	Connecting Route
M101	North	V-7 or V-9
M102	West	V-6-8
M103	South, Southwest	V-173-191
M104	South	V-53-128-171
M105	South, Southeast	J-99
M106	South, Southeast,	J-146
M107	East	V-6-10
M108	Northeast	V-116-218

Again, the Milwaukee arrival and departure routes change as the traffic flow changes at O'Hare. In this case the arrival and departure routes reverse their roles.

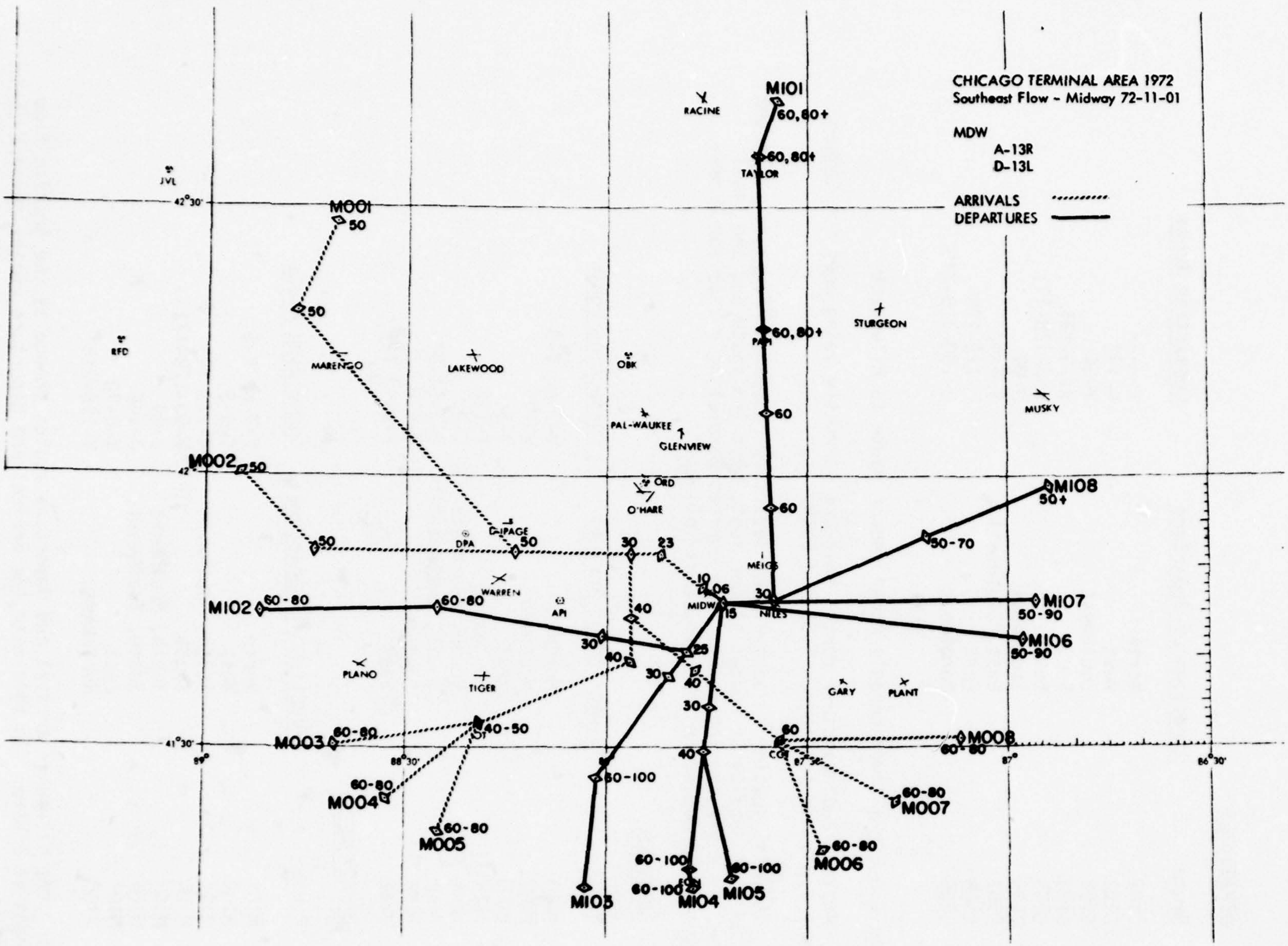


Figure 5.56 Chicago Terminal Area-1972 RNAV Routes, Midway, Southeast Flow

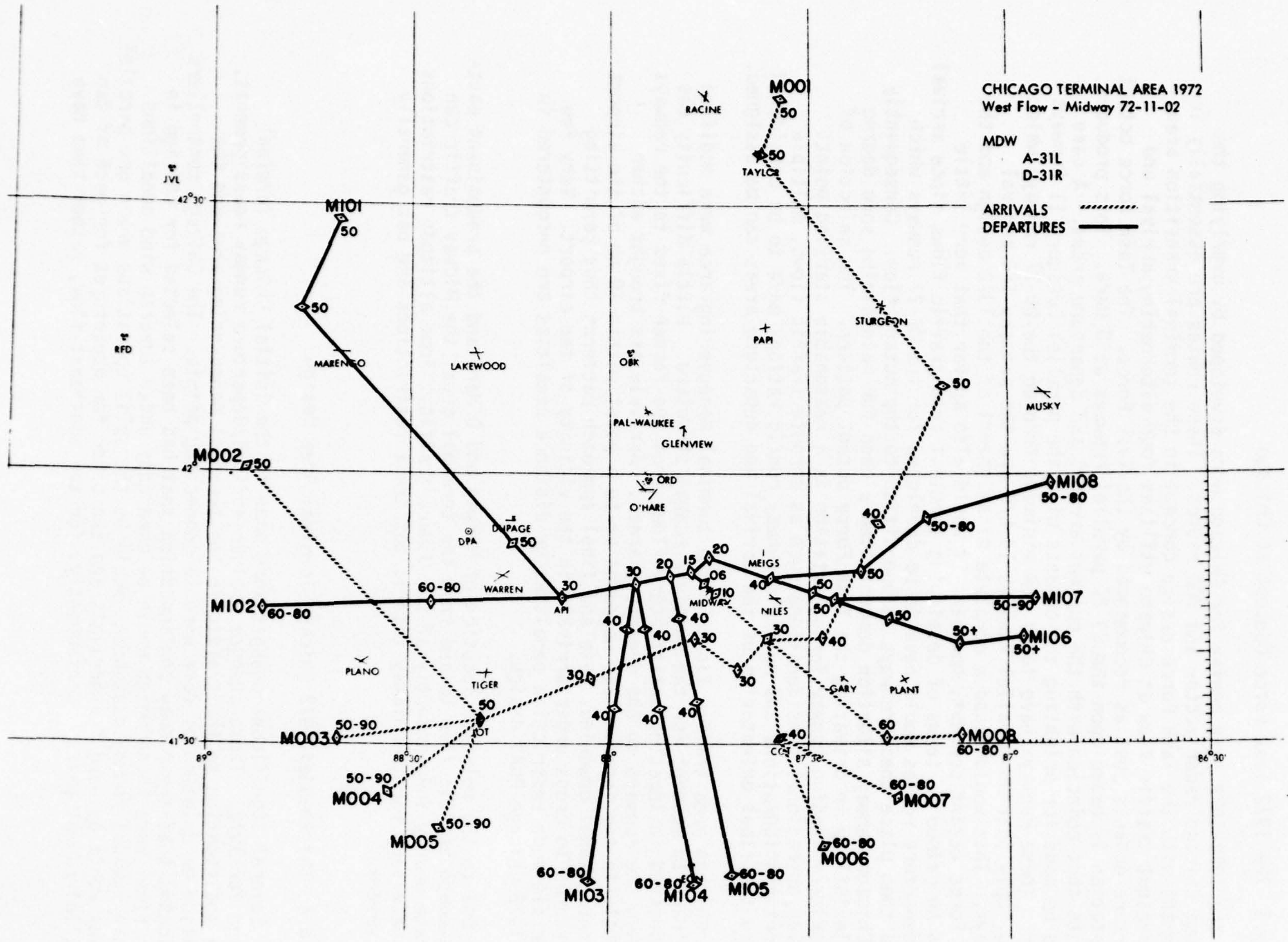


Figure 5.57 Chicago Terminal Area-1972 RNAV Routes, Midway, West Flow

5.1.6.3 The 1972 Task Force Concept at Chicago

The 1972-1977 RNAV routes for Chicago were developed by overlying the present Chicago radar vector and VOR routes. These routes are essentially in agreement with the Task Force design concept in the terminal transition area. The present traffic flow at Chicago utilizes four alternating arrival and departure octants just as recommended by the Task Force. The Task Force octant orientation is based upon the 09-27 parallel runways at O'Hare. This produces octants that coincide with the current arrival and departure areas. A case could be made for orienting the octants with the parallel Category II Runways 14-32. These runways have lower IFR minimums than do the 09-27 runways which would imply that the parallel Runways 14 L/R are the primary IFR arrival runways. This would cause a complete misalignment of the 1972 design and the Task Force octant concept, however. It would also appear that very little would be gained in terms of developing terminal area traffic flows since arrival and departure routes would have to be developed for the 09-27 runways which would then place these runways in opposition to the octant flow. Consequently the Chicago runway situation demonstrated a need for maintaining some degree of flexibility in orienting the Task Force octant pattern. The selection of the primary landing runway for orientation is a reasonable starting point; however, operational considerations such as enroute traffic flows, multiple airport configurations and multiple runway configurations have to be considered before the final orientation of the arrival and departure areas can be assigned.

Chicago area traffic flows in the terminal maneuvering area were modified at O'Hare to account for the multiple runway structure. Little difficulty was encountered in locating satisfactory flows from the feeder fixes to the runways or from the runways to the departure areas. Arrivals are brought either directly to the intermediate waypoint or to a point within 10 nm of the airport in conventional downwind, base and final approach patterns thus permitting departures to cross under arrivals in the vicinity of the airport. Very few major altitude restriction penalties or distance penalties are encountered in the 1972 Chicago RNAV design.

Due to the relative location of Midway and O'Hare and the predominant east-west-south traffic flow to and from the terminal area, the Midway traffic can operate nearly independently of the O'Hare traffic. Some altitude restrictions are necessary for the Midway traffic but these restrictions are not generally too severe.

5.1.6.4 The Amended 1972 Chicago Terminal Area Design

Several significant changes were made to the initial Chicago Terminal design for 1972. These changes include arrival/departure runway reassignments, some modification to the traffic in the terminal maneuvering area and the addition or deletion of some enroute connecting points. The Chicago controllers indicated that the runway configuration that had been selected for Chicago in both flows were those which would be used only under adverse wind conditions. A more typical runway assignment would be the split operations where one parallel runway would be used for arrivals and the other for departures for each of two parallel runway pairs. Consequently, for the southeast flow, rather than have

all arrivals on Runways 14 R/L and departures on 09 R/L, the runway assignments were changed to arrivals on 09R and 14L, and departures on 09L and 14R as shown in Figure 5.58. For the northwest flow configuration the runway patterns were changed from arrivals on Runways 27 R/L and departues on 32 R/L to arrivals on 27 R and 32 L and departures on 27L and 32 R as shown in Figure 5.59. This change in runway assignments produced a corresponding requirement to change the terminal maneuvering area traffic patterns. In addition some other changes were suggested for the terminal maneuvering area routes.

In the previous design for the southeast flow, Figure 5.54, traffic arriving from the northeast were shown to proceed from Sturgeon Intersection on a modified downwind leg to intercept the base leg five miles from the final approach course. A more representative flight path is shown in Figure 5.58. The aircraft proceed from Sturgeon Intersection to a point on the downwind leg near Pal-Waukee Airport as shown on route 001. In the area southeast of the airport, the previous design showed traffic arriving over Chicago Heights VORTAC. In actuality the aircraft proceed from the enroute structure to a feeder fix near Gary Airport from where they proceed direct to O'Hare Airport. The high altitude arrival in this area was changed also. Route 002, which lies north of those shown on the previous design (Figure 5.54) was added while two other routes from the previous design were deleted. For the departure west of Chicago one route, number 110, was added. This route goes to Dubuque VORTAC.

Corresponding changes were made in the northwest flow configuration for Chicago O'Hare. Again the terminal maneuvering area routes were changed to reflect the reassigned arrival and departure runways. In addition northeast arrivals were brought into Papi Intersection where they make a base leg entry for the approach to Runway 27R. In the original design the aircraft were brought into the base leg from Sturgeon. Southeast arrivals were again brought into the terminal area over Gary Airport rather than Chicago Heights VORTAC as mentioned in the southeast flow design. Enroute connecting points were changed to coincide with those in Figure 5.58. Also the westbound departure route to Dubuque VORTAC was added to the northwest flow configuration.

5.1.7 New York

5.1.7.1 Characteristics of the New York Terminal Area

Airport Configuration

Certainly the most distinctive characteristic of the New York Terminal Area is the presence of three major airports within the terminal complex. In addition there are several satellite airports which are served by the Common IFR Room (CIFRR). The following traffic count shown in Table 5.4 was obtained from the 1971 Peak Day IFR records. White Plains (HPN) and Teterboro (TEB) both generate a significant fraction of the Kennedy (JFK) LaGuardia (LGA) and Newark (EWR) traffic. Consequently, their traffic was considered significant in determining the overall New York design. Morristown (MMU) and Islip (ISP) were included to account for satellite traffic east and west of the three major airports.

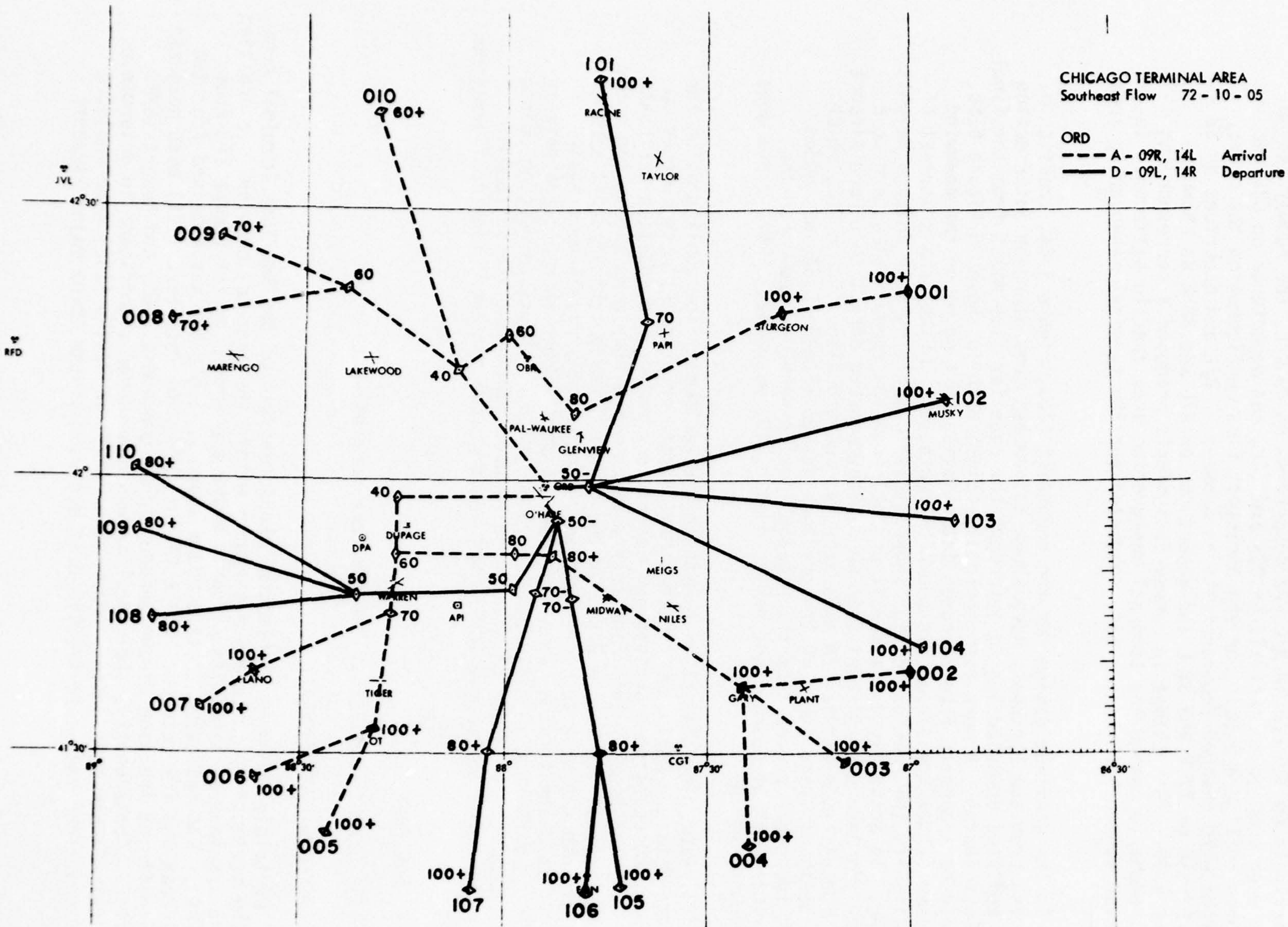


Figure 5.58 Amended Chicago Terminal Area - 1972 RNAV Routes, O'Hare, Southeast Flow

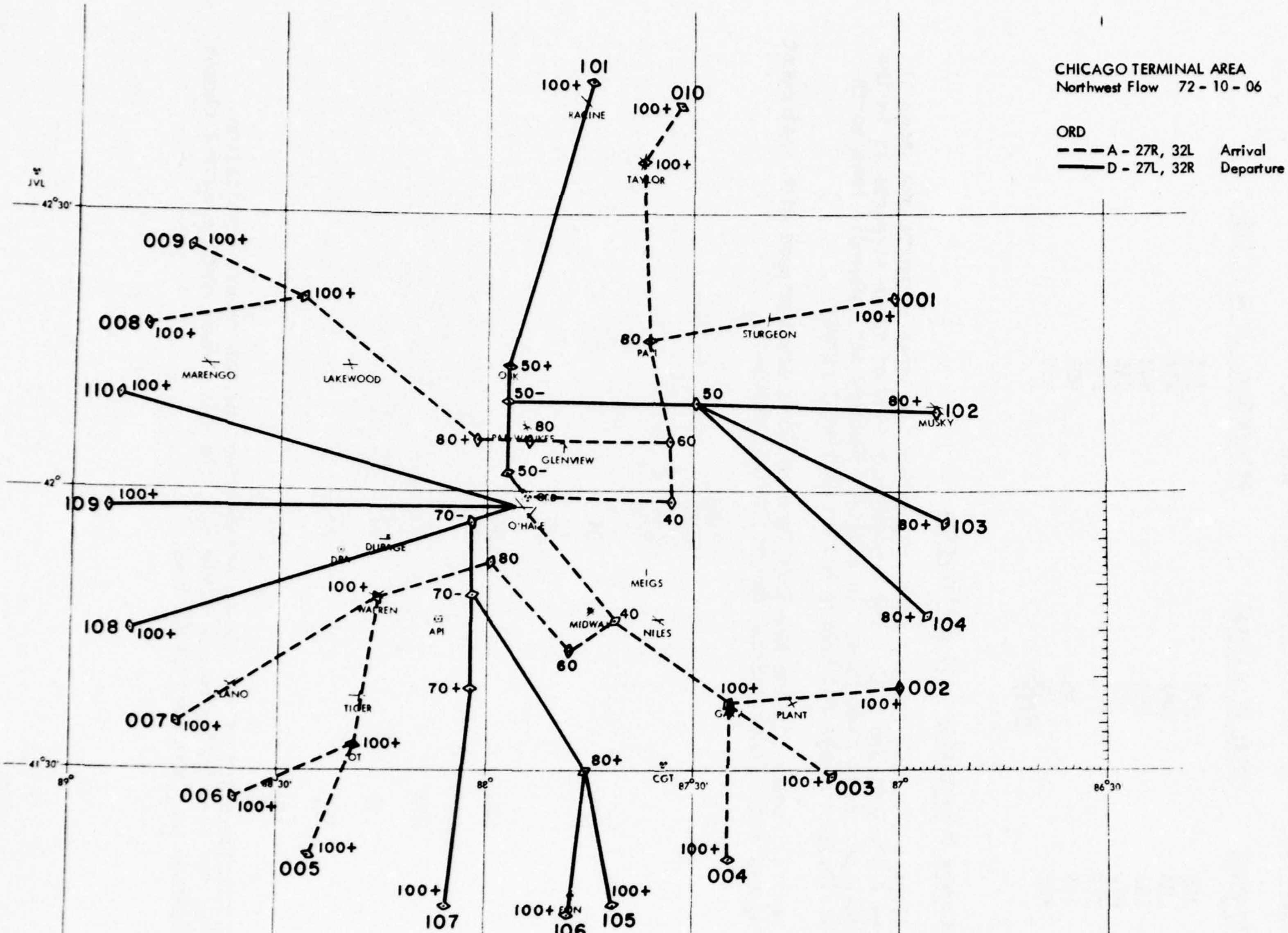


Figure 5.59 Amended Chicago Terminal Area - 1972 RNAV Routes, O'Hare, Northwest Flow

TABLE 5.4 IFR TRAFFIC OPERATIONS AT NEW YORK

AIRPORT	TOTAL OPERATIONS	PERCENTAGE LOW ALTITUDE
JFK	876	22%
LGA	882	43%
EWR	591	44%
HPN	179	63%
TEB	119	77%
ISP	45	96%
MMU	20	85%
	2712	

Runway Orientations and Utilization

Airport diagrams for the three major New York area airports are shown in Figures 5.60, 5.61 and 5.62. The predominant flow of these airports is in the northeast-southwest direction. In addition Kennedy and LaGuardia have northwest-southeast runways and Newark has an east-west runway.

Several runways in the New York Terminal Area are equipped with instrument landing systems. These include the following runways:

JFK	31R/L 04R 13L 22L
LGA	04 13 22
EWR	04R/L 22L
HPN	16
ISP	06
MMU	23
TEB	06

After consideration of the runway orientation and the runway utilization figures for June 1972 shown in Table 5.5, the two runway configurations chosen for further analysis were as follows:

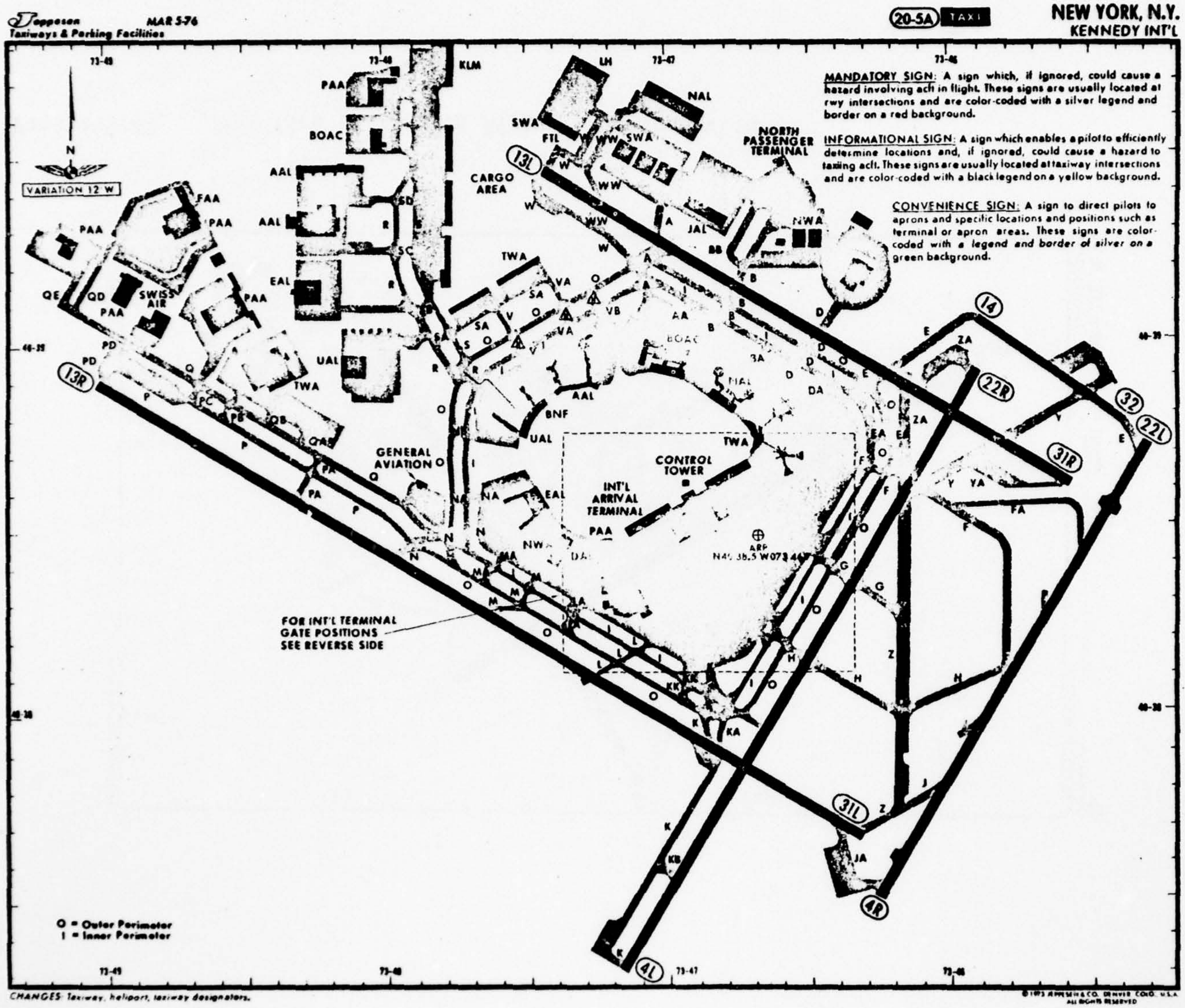


Figure 5.60 New York Kennedy International Airport Configuration

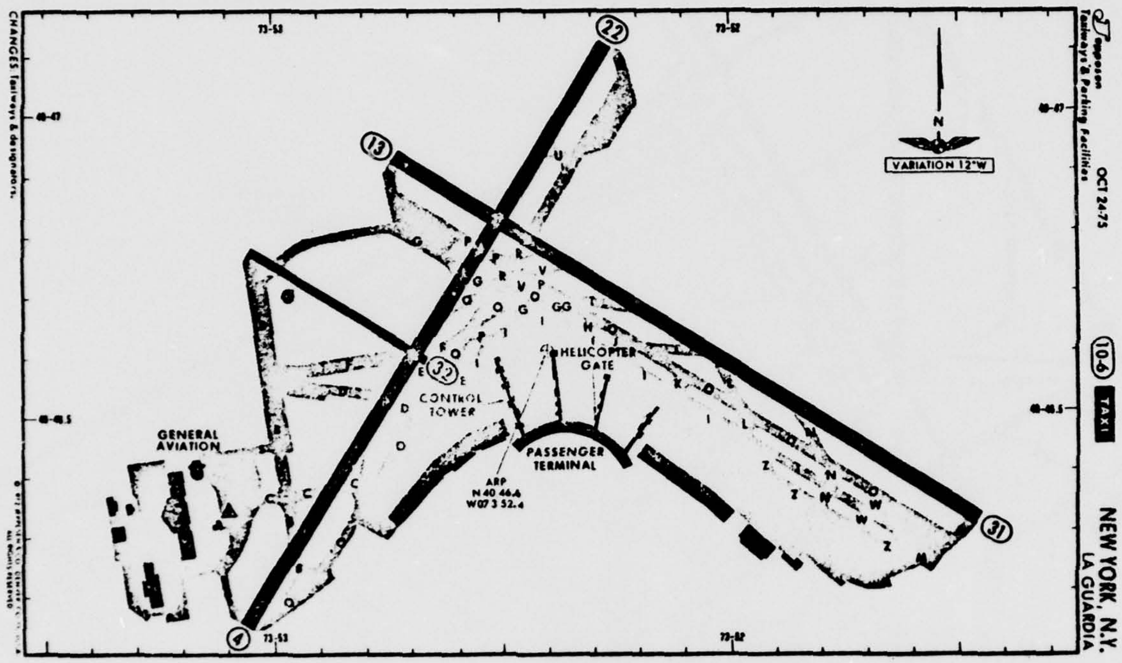


Figure 5.61 New York La Guardia Airport Configuration

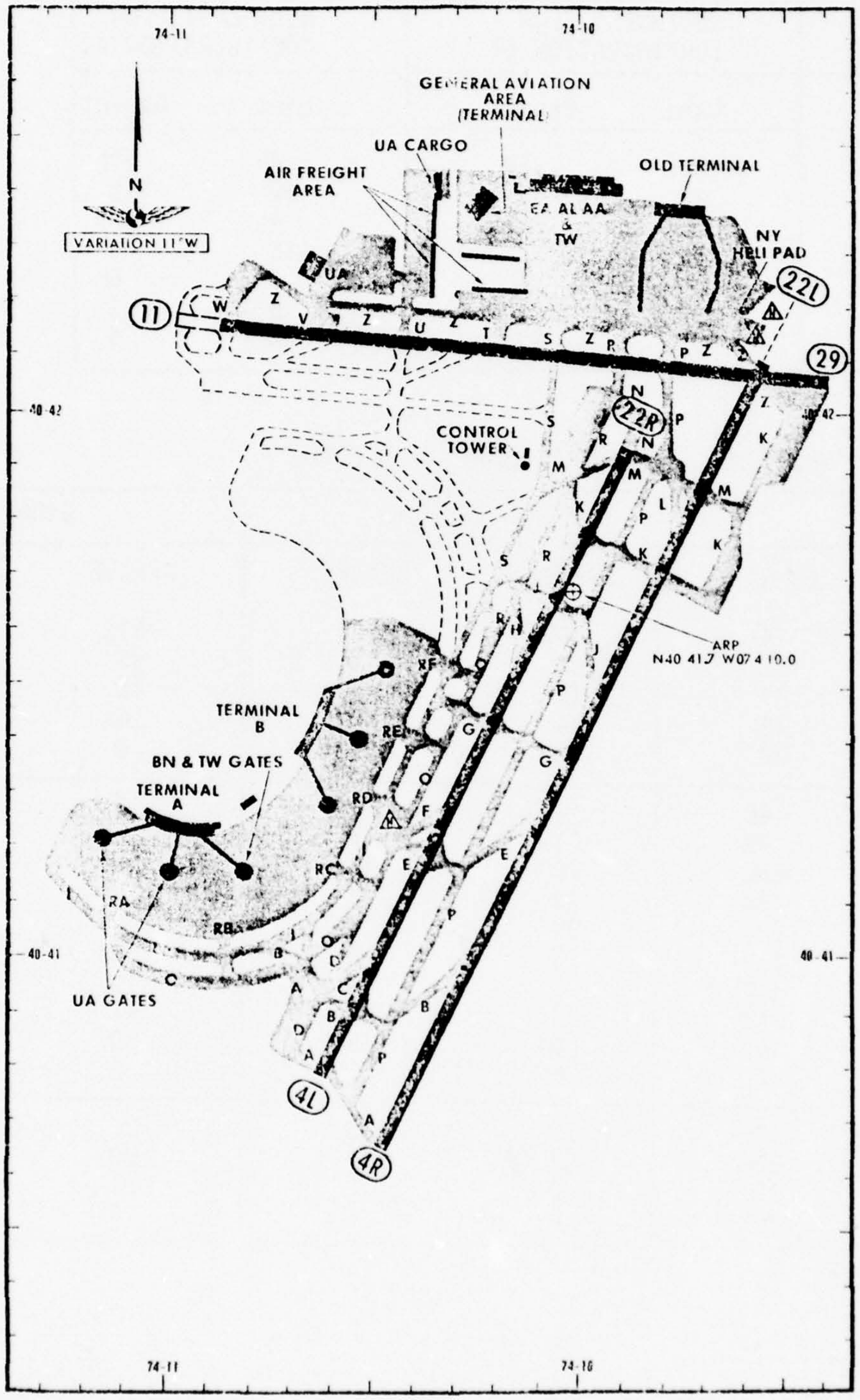


Figure 5.62 Newark Airport Configuration

RUNWAY CONFIGURATION USED IN ANALYSIS

AIRPORT	SOUTHWEST FLOW CONFIGURATION #1		NORTHEAST FLOW CONFIGURATION #2	
	Land	Depart	Land	Depart
JFK	22L	22R	4R	31L
LGA	22	31	22	13
EWR	22R	22L	4L	4R
HPN	16	23	16	5
TEB	19	24	6	6
ISP	24	24	6	6
MMU	23	23	5	5

TABLE 5.5 PERCENTAGE RUNWAY UTILIZATION

		Air Carrier		Other	
AIRPORT	RUNWAY	ARRIVE	DEPART	ARRIVE	DEPART
LGA	4	9%	18%	11%	16%
	22	62	1	55	11
	31	15	24	18	22
	13	14	57	16	49
	32	0	0	0	3
JFK	4L	--	1	7	5
	4R	11	7	1	1
	13L	28	18	4	13
	13R	13	19	34	16
	22L	28	12	3	1
	22R	2	5	32	14
	31L	5	4	19	19
	31R	13	8	--	11
	14	0	18	0	14
	32	0	8	0	6
EWR	4L	33	33	26	22
	22R	67	67	50	49
	11	0	0	21	2
	29	0	0	3	27

It can be seen that LaGuardia traffic often lands to the southwest even when other airports are using the northeast configuration. This is due to noise abatement procedures applied by the LGA controllers. The widely distributed JFK runway usage is also due to noise abatement procedures. Runway configurations at JFK are changed every 8 hours whenever possible regardless of the existing wind conditions. Consequently, traffic at JFK is quite uniformly distributed among the major instrument runways.

Terminal Area Traffic Flows

The current terminal traffic flows are depicted in Figure 5.63 along with the octant traffic flow concept which is to be utilized in the 1982 terminal design. It can been seen in Figure 5.63 that the traffic flow does depart from the octant concept in several areas. The arrival and departure fixes for each of the three major airports is listed in Table 5.6. Also listed in Table 5.6 are the current control jurisdictions used in New York. At each of the three major airports there is a final controller position also. Traffic for TEB and MMU generally use the Newark traffic flows and controllers. Similarly, Islip traffic generally uses Kennedy routes and controllers for most of the approaches or departures. Exceptions to this statement may occur when the aircraft is a single engine aircraft. These aircraft can fly at 3,000 feet which is below the normal traffic patterns.

TABLE 5.6 ARRIVAL AND DEPARTURE FIXES

ARRIVALS	DIRECTION	CONTROL JURISDICTION
JFK		
Bohemia	NE	Bohemia Controller
Carmel VOR	N (minimal traffic)	Bohemia Controller
Empire	W	Empire Controller
Southgate	S	Southgate Controller
LGA		
Carmel VOR	NE, N	Carmel Controller
Penwell	SW, W	Penwell Controller
Robinsville VOR	SSW, S	Robinsville Controller
EWR		
Monroe	N, NE, NW	Monroe Controller
Budd Lake	W,	Budd Lake Controller
Princeton	SW, S	Princeton Controller

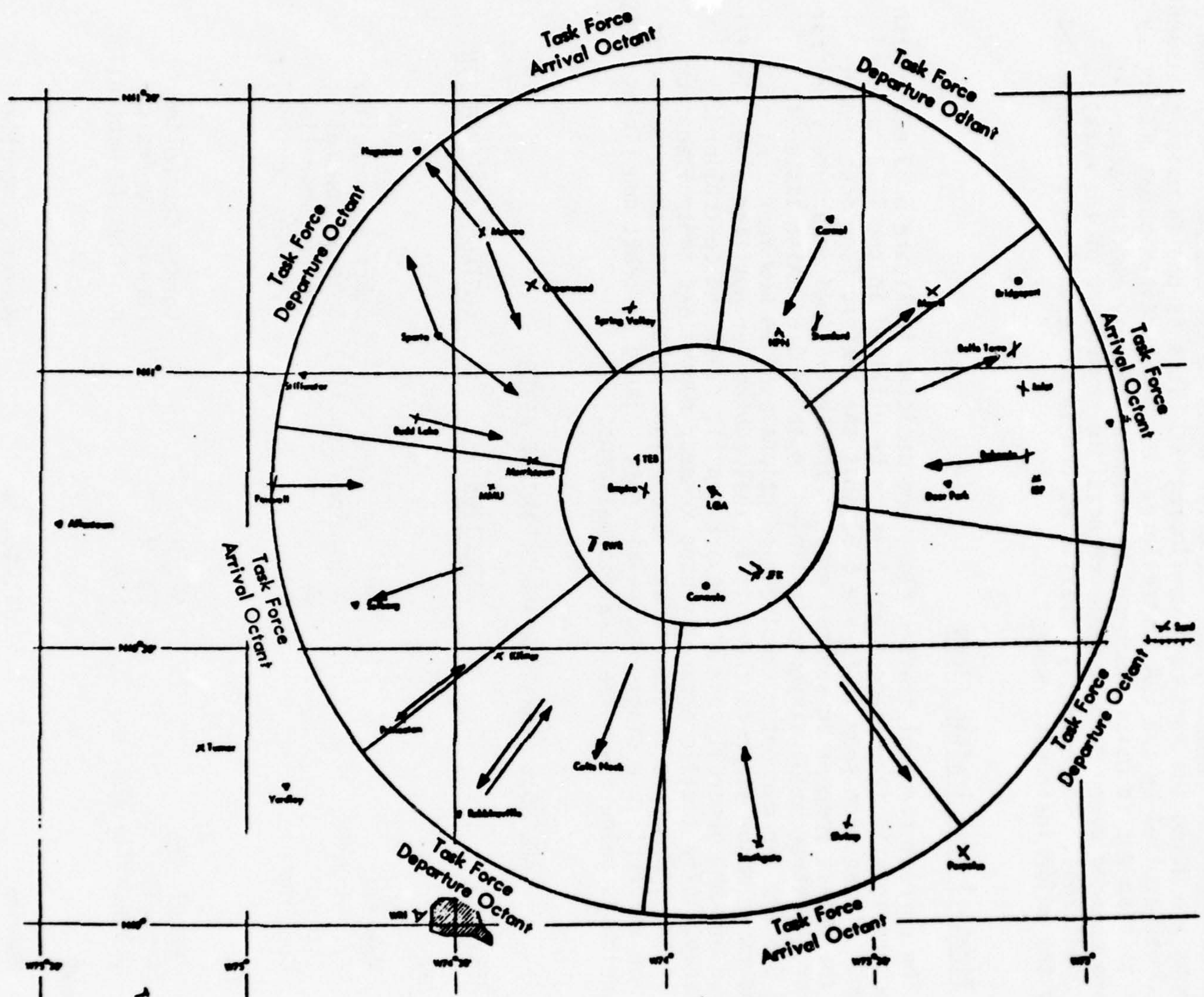


Figure 5.63 Current New York Traffic Flow vs. the Task Force Octant Concept

TABLE 5.6 ARRIVAL AND DEPARTURE FIXES (Continued)

DEPARTURES	DIRECTION	CONTROL JURISDICTION
JFK		
Belle Terre	NE	JFK Departure
Huguenot VOR	NW	JFK Departure
Robbinsville	SW	Southwest Departure
Coyle VOR	SW	Southwest Departure
Shrimp	SE	JFK Departure
Porpoise	SE	JFK Departure
Sardine	SE	JFK Departure
LGA		
Merrit	NE	LGA North Departure
Greenwood	NW	LGA North Departure
Solberg VOR	SW	LGA South Departure
Robbinsville VOR	S	LGA South Departure
Colts Neck VOR	S	Southwest Departure
EWR		
Merrit	NE	EWR Departure
Sparta VOR	NW	EWR Departure
Solberg VOR	SW	EWR Departure
Colts Neck VOR	S	Southwest Departure

Enroute Traffic Flow

High altitude and low altitude traffic distribution diagrams were constructed for the New York area. These diagrams are shown in Figures 5.64 and 5.65. The traffic on these diagrams represents about 70% of the peak day traffic of Table 5.4. Some 30% of the traffic is unaccounted for in these traffic diagrams.

5.1.7.2 The 1972 New York Terminal Area Design

The routes shown in Figures 5.66 and 5.67 are those used in the current radar vector-VOR environment of New York. These routes are extended from the arrival or departure fix to the periphery of a 47 nm circle centered 2 nm west of LGA. These diagrams were constructed from current SID routes and radar vector arrival routes as described in the Common IFR Room Standard Operating Procedures Manual.

Due to the high density of routes in the New York area it was determined that the addition of RNAV routes within the terminal maneuvering area would not improve traffic flow in the 1972 configuration. Consequently, the 1972 design contains conventional routes with RNAV routes superimposed upon these conventional VOR and radar vector routes.

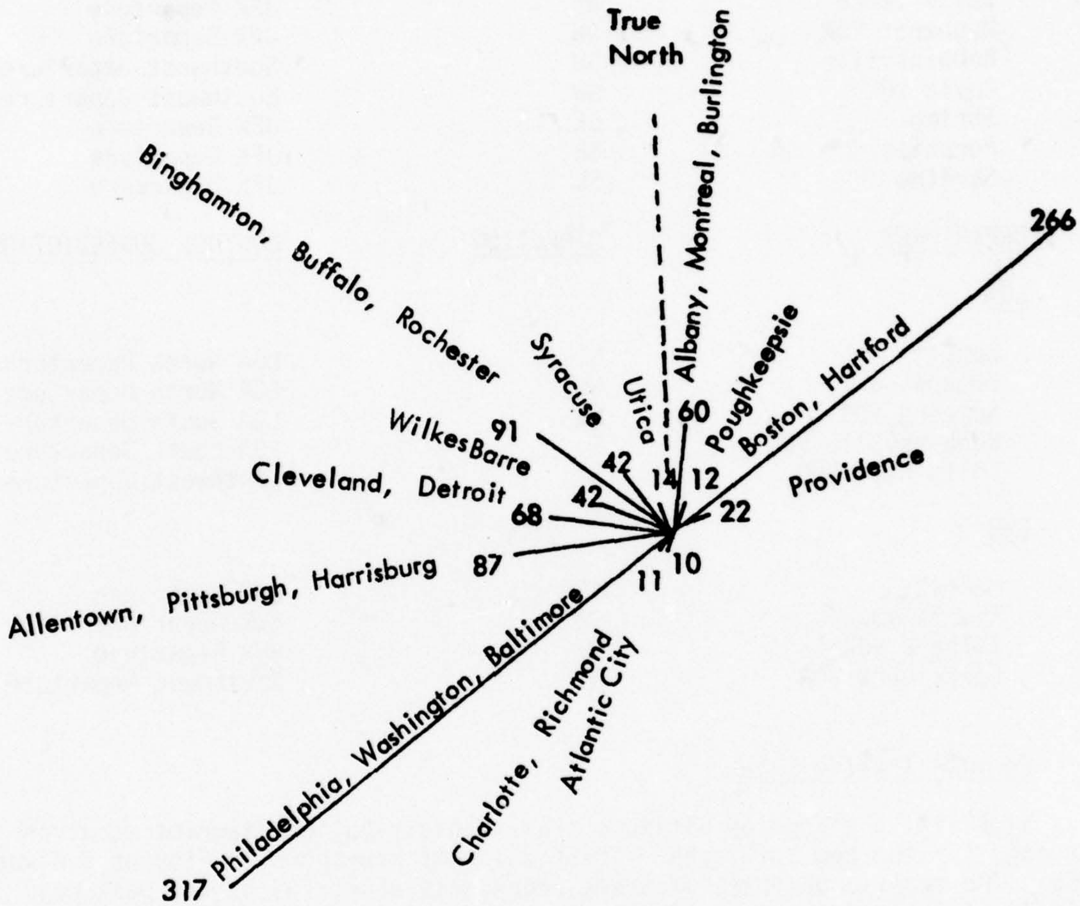


Figure 5.64 New York Low Altitude Traffic Distribution Diagram

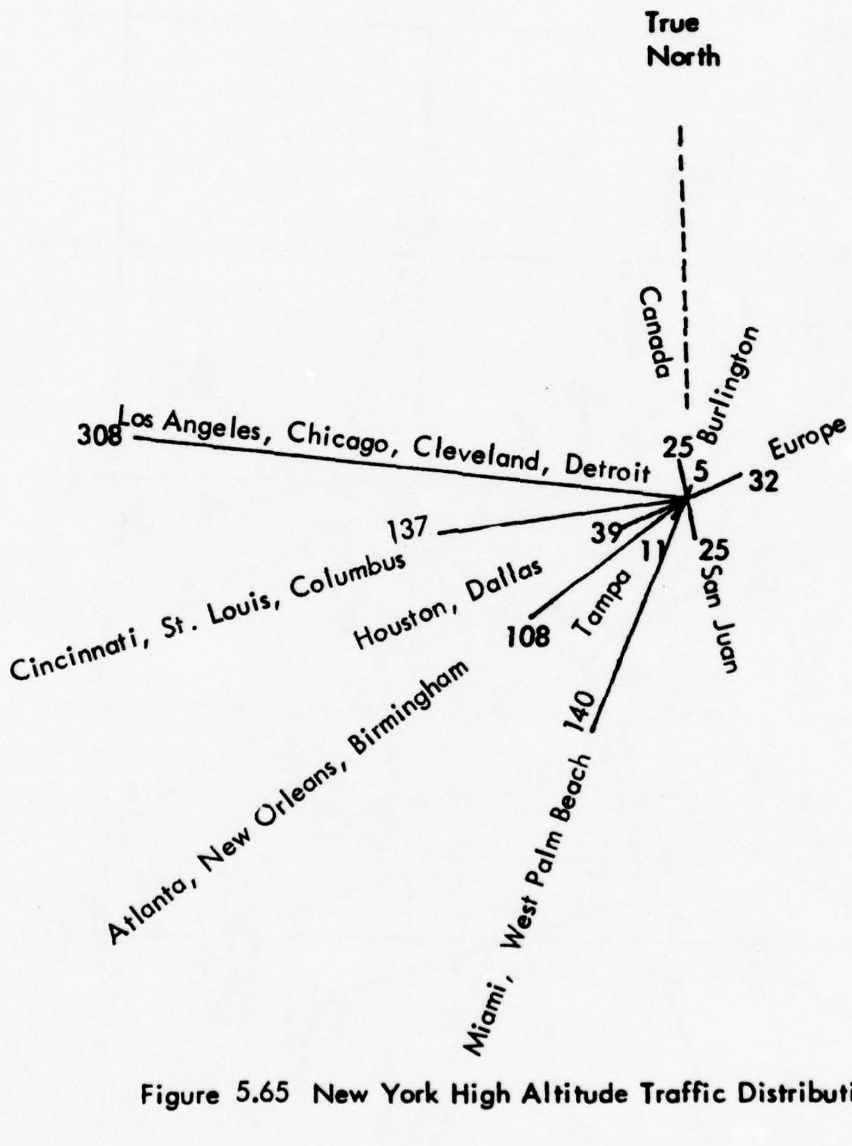


Figure 5.65 New York High Altitude Traffic Distribution Diagram

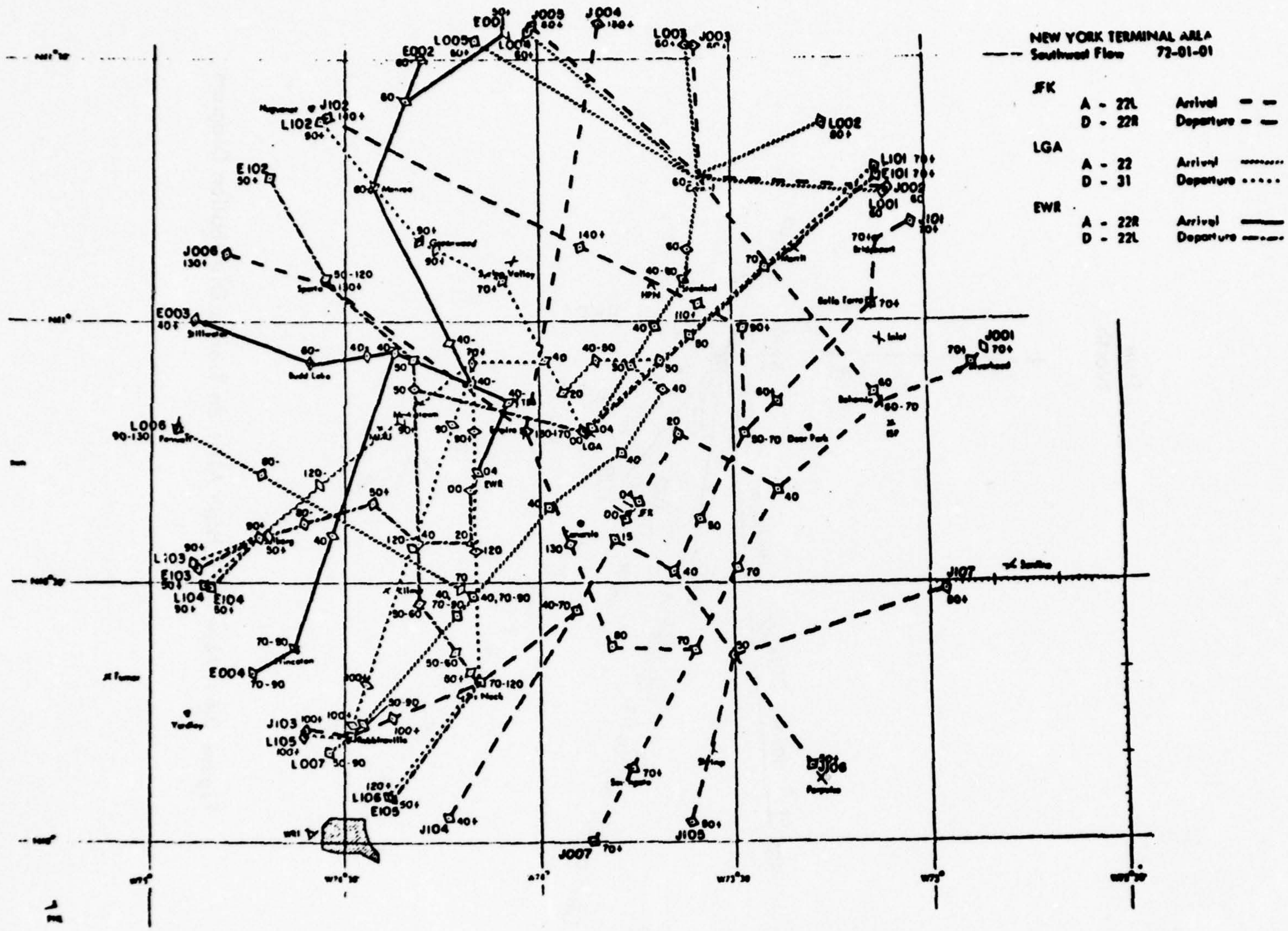


Figure 5.66 New York Terminal Area-1972 RNAV Routes, Southwest Flow

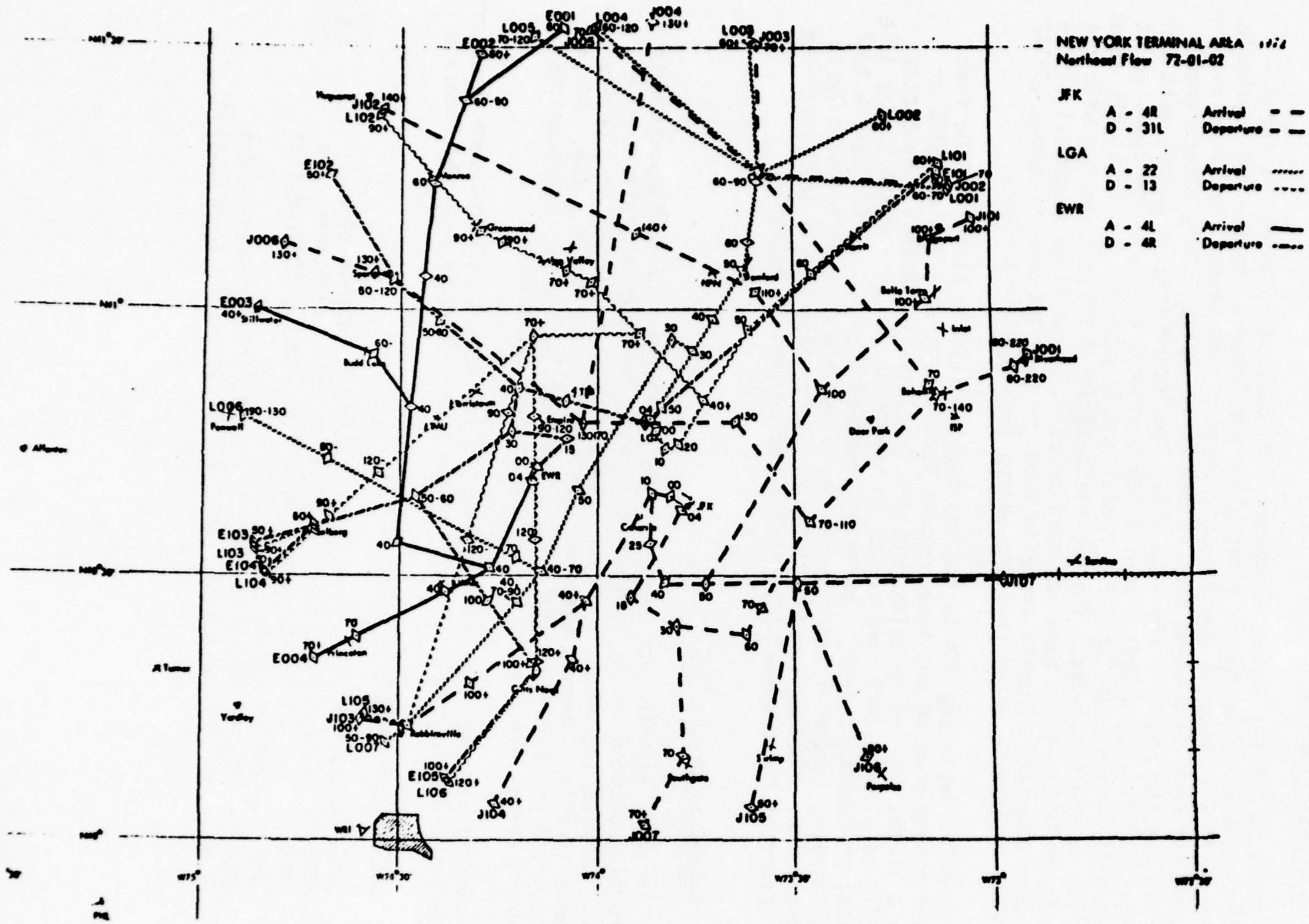


Figure 5.67 New York Terminal Area-1972 RNAV Routes, Northeast Flow

Southwest Flow - JFK

Arriving traffic in the southwest flow configuration enters the JFK traffic pattern at the feeder fixes which are Bohemia, Empire and Southgate. Empire traffic is brought considerably south of the airport in order to give the aircraft room to descend from 13,000 ft at Empire. Only pressurized aircraft use the Empire arrival to JFK. The Empire traffic merges with the Southgate traffic on a left downwind leg southeast of JFK. The downwind is essentially on the Deer Park 221° radial and is parallel to runway 22L about 13 miles to the southeast. The Empire-Southgate traffic is merged with the Bohemia arrivals at the base leg turning point about 13 nm southeast of the IF. Unpressurized aircraft arriving from the west proceed to Carmel VORTAC and then to Bohemia where they are merged with Bohemia arrivals.

Traffic departing JFK to the southwest initially climb to 1500 feet on the runway heading and then proceed direct to either Coyle VORTAC or make a slight dog leg to Colts Neck and Robbinsville VORTACs. East coast traffic is given a left turn vector to intercept Victor 139-308 to Sea Isle (south) or Hampton (north). North and northeast bound traffic make a 180° turn, keeping inside of the downwind arrivals, and proceed to Belle Terre intersection. Northwest and west bound traffic also make a 180° left turn and intercept the Huguenot 308° radial and proceed to Huguenot.

Northeast Flow - JFK

Arriving traffic over Empire in the Northeast Flow Configuration is currently vectored to the east to merge with the Bohemia arrivals on a right downwind leg which is offset from the runway about 13 nm. Empire-Bohemia traffic is merged with Southgate traffic on the base leg. Again pressurized aircraft from the west arrive over Empire and unpressurized aircraft arrive over Carmel VORTAC and proceed to Bohemia.

Departure traffic from runway 31L follow essentially the same departure route as in the Southwest Flow after making a left turn near the Canarsie VOR.

Enroute Connecting Points - JFK

J001 - Victor 16 to Riverhead to Bohemia Intersection
J002 - Victor 34 to Carmel VORTAC to Bohemia Intersection
J003 - Victor 487 to Carmel VORTAC to Bohemia Intersection
J004 - Victor 157 to Empire Intersection
J005 - Victor 483 to Carmel VORTAC to Bohemia Intersection
J006 - Victor 36-188 to Sparta VORTAC to Empire Intersection

Departures - JFK

J101 - Belle Terre Intersection to Bridgeport VOR to Victor 99
J102 - Huguenot VORTAC to Victor 252, Jet 36, 95, 63, 552
J103 - Colts Neck VORTAC to Robbinsville VORTAC to Victor 276
J104 - Direct to Coyle VORTAC on Victor 16
J105 - Intercept Victor 139-308 or Jet 121 to Sea Isle VORTAC
J106 - Proceed outbound on the JFK 154° radial to Porpoise and Tuna Intersections for Jet 63 for an oceanic departure
J107 - Intercept Victor 139-308 or Jet 121 to Hampton VORTAC

La Guardia Arrivals - Both Configurations

La Guardia is situated in an interesting location as far as traffic flow is concerned. La Guardia has limited airspace to the east due to Newark, the west due to JFK and the north due to White Plains. As a consequence, the north arrivals over Carmel must travel through the White Plains area and the west arrivals are given a corridor through Newark airspace. As was mentioned previously, only arrivals to Runway 22 were considered at La Guardia due to noise abatement constraints. However, there is a difference in the arrival flow patterns for La Guardia due to the influence of the JFK departure runway. This situation represents in a small way the interrelationships which exist in a complex terminal area such as New York.

Eastbound arrivals over Penwell merge with northbound arrivals from Robbinsville at a point about 25 nm southwest of the airport. They then proceed on a long downwind leg to intercept a base leg about 5 nm from the intermediate fix. When JFK is using runway 31 for departures, the La Guardia arrivals make a right hand traffic pattern to remain clear of the JFK departures. Otherwise, a left hand traffic pattern is used. The Carmel arrivals merge with the Penwell-Robbinsville traffic at the intermediate fix.

La Guardia Departures - Runway 31

All departures from Runway 31 climb on a heading of 330° to 2000 feet and then turn to intercept their departure route. North and northeast bound traffic turn right to intercept the La Guardia 060° radial to Merrit Intersection. Northwest bound traffic proceeds on a 330° heading until intercepting the Deer Park 308° radial to Greenwood Intersection whereupon they intercept the Huguenot 152° radial and proceed to Huguenot. Southwest and southbound traffic have three routes available for departure.

1. Left turn to intercept the Solberg 061° radial to Solberg
2. Left turn to intercept the Robbinsville 30° radial to Robbinsville
3. Left turn to intercept the Colts Neck 012° radial to intercept the 047° radial of Millville VORTAC.

La Guardia Departures - Runway 13

After climbing to 1000 ft and making a left turn, the Runway 13 departures use essentially the same departure paths as the Runway 31 departures. Some

penalty is paid by the southwest departures as they must execute a nearly 270° turn before proceeding to their departure fix.

Enroute Connecting Points - La Guardia Arrivals

L001 - Victor 34 (westbound) to Carmel VORTAC
L002 - Victor 3-292 to Carmel VORTAC
L003 - Victor 487 to Carmel VORTAC
L004 - Victor 483 to Carmel VORTAC
L005 - Victor 34 (eastbound) to Carmel VORTAC
L006 - Victor 232 to Penwell Intersection
L007 - Victor 123-157-312 to Robbinsville

Departures

L101 - Merrit Intersection to Victor 433, 467, 475
L102 - Huguenot VORTAC to Victor 252, Jet 36, 95, 63 and 552
L103 - Solberg VORTAC to Victor 30
L104 - Solberg VORTAC to Victor 3
L105 - Robbinsville VORTAC to Victor 276
L106 - Colts Neck 012° radial to the Millville 047° radial to Victor 467

Newark Arrivals - Southwest Flow

Princeton arrivals proceed on a long downwind leg in a right hand traffic pattern. The downwind leg is offset about 15 nm west of the airport. Princeton and Budd Lake traffic are merged at the base leg turning point and merged with Monroe arrivals on the base leg about 6 nm from the IWP. Newark arrivals are tunneled under most La Guardia and JFK traffic in the terminal area.

Newark Arrivals - Northeast Flow

The northeast flow is almost the reverse of the southwest flow as now Monroe arrivals proceed on a long downwind for a left hand pattern. The downwind leg is generally greater than 12 nm west of the airport. Budd Lake Traffic merges with Monroe traffic abeam of the airport. This flow merges with the Princeton arrivals at the IWP.

Newark Departures - Southwest Flow

Runway 22 departures climb on a heading of 190° to 2000 ft whereupon they turn toward their departure fixes. Northeast and northbound traffic turns right to 010° and proceeds north to intercept the La Guardia 116° radial to La Guardia VORTAC and then outbound on the 060° radial to Merrit Intersection. Northwest bound traffic turns right to 010° and proceeds north to intercept the Sparta 144° radial to Sparta VORTAC and then outbound on the 342° radial (Victor 273). Southwest bound traffic proceeds either west to intercept the Solberg 085° radial to Solberg VORTAC or south to intercept the Colts Neck 335° radial intercepting the Millville 047° radial.

Newark Departures - Northeast Flow

Departures from Runway 4 make a right turn to 060° for noise abatement, then turn left to 290° to avoid high building obstructions on Manhattan. After proceeding west about 6 nm they can turn to their departure fix. The remainder of the departure design is similar to the southwest flow departure.

Enroute Connecting Points

Arrivals

E001 - Victor 489 - 205 to Silky Intersection to Monroe Intersection
E002 - Victor 249 to Monroe Intersection
E003 - Victor 226 to Stillwater VORTAC to Budd Lake Intersection
E004 - Victor 433 to Princeton Intersection

Departures

E101 - Merrit Intersection to Victor 433, 467, and 475
E102 - Sparta VORTAC to Victor 273 to intersect Huguenot departure routes Victor 252, Jet 36, 95, 63 and 552
E103 - Solberg VORTAC to Victor 30
E104 - Solberg VORTAC to Victor 3
E105 - Colts Neck 335° radial to the Millville 047° radial which is Victor 467

5.1.7.3 The 1972 Task Force Concept at New York

The New York terminal area represented the most complex terminal area route structure encountered in the seven terminal areas for which RNAV designs were created. RNAV routes were developed for each of the three major airports. Due to the high incidence of crossing routes and the limited airspace with which to work, the RNAV routes were designed to overlie the current radar vector/VOR routes for both arrivals and departures. No difficulty was encountered in developing the RNAV routes in this manner. Very little airspace was available in which to develop RNAV routes that were independent of the current vector routes but which would serve an area of significant traffic demand. Consequently, the practice of overlying the vector routes was considered to be the most desirable way to introduce RNAV routes into the New York terminal area.

New York area traffic in the terminal transition area was not well aligned to the octant flow concept of the Task Force. Most of the Task Force octants contain both arrival and departure traffic from one or more of the three major airports. Often the same navigation facility is used for both arrival and departure traffic that is separated by altitude. For example Sparta VORTAC is used by the Kennedy Empire arrivals and by the westbound Newark departures. The Kennedy arrivals are kept above the Newark departures. Similarly in the southwest part of the terminal area Robbinsville VORTAC is used by La Guardia arrivals from the south and is also used by departures to the southwest from Kennedy and La Guardia. Consequently the 1972 New York traffic flow did not

permit any development of the Task Force octant flow concept during this initial RNAV implementation time phase.

Traffic flow in the terminal maneuvering area at New York is complicated by the necessity to have three terminal maneuvering areas, one for each airport. In some flow configurations these maneuvering areas can be in conflict. This situation often occurs between Kennedy and LaGuardia traffic when Runways 31 L/R are used for Kennedy departures or Runways 13 L/R are used for Kennedy arrivals and LaGuardia is using Runways 04 or 22. Special airspace assignments must be made during these operations.

Kennedy arrivals and departures use conventional terminal maneuvering area procedures but they are restricted to using the airspace to the east of the Kennedy airport. Newark arrivals also use standard terminal area traffic procedures but they must use the airspace to the west of the Newark airport only. Newark departures have a rather complex set of turns to accomplish while they are making a noise abatement climb over the Hudson River. La Guardia departures are often turned quickly after take off in order to avoid Kennedy and Newark arrivals on final approach. Consequently, very little opportunity exists to apply the Task Force terminal maneuvering area procedures at La Guardia.

5.1.7.4 The Amended 1972 New York Terminal Area Design

After reviewing the 1972 designs for New York, Figures 5.66 and 5.67, the New York controllers stated that the routes as depicted in these figures were generally an accurate representation of the VOR/radar vector procedures that were in use in New York in that time period. Consequently, it was not considered necessary to develop amended New York route structures for 1972 since they are adequately represented in Figures 5.66 and 5.67.

5.2 1972-1977 2D RNAV DESIGN ANALYSIS

The analysis of the 1972-1977 terminal area designs consisted of two major tasks. The first of these tasks included the creation of the designs for the seven terminal areas and a comparison of the designs to the Task Force Model. The methodology is described in Section 4. In their recommendations for RNAV terminal designs in the 1972-77 time period, the Task Force suggested that the 1972-1977 designs adhere as closely as possible to the Task Force terminal design concept. They also suggested that whenever possible the RNAV routes should be designed to overlie current optimum radar vector routes. In the following paragraphs the seven terminal designs are analyzed with respect to these recommendations of the Task Force.

The second task in the analysis of the 1972-1977 terminal designs consisted of a real time simulation of the New York Kennedy terminal area for 1972 [13]. The simulation was designed to evaluate the ability of the controller and the user to operate in a mixed radar vector/VOR traffic and RNAV traffic environment during the 1972-77 RNAV transition period. The simulation of the 1972-1977 New York-Kennedy route structure consisted of varying the percentage of RNAV traffic and measuring the effects upon controller workload and the

control procedures. Simulation runs using five controller groups and four ratios of RNAV traffic levels to total levels were performed.

5.2.1 Application of the 1972-1977 Task Force Concepts

5.2.1.1 Terminal Transition Area Routes

The most successful technique for developing RNAV terminal area routes in the initial implementation time period was the Task Force recommended technique of overlying RNAV routes on current radar vector/VOR routes. This technique was successfully applied in all seven terminal areas for both the original designs and the amended designs. An analysis of the terminal area traffic distributions and the location of present routes indicated that the current vector/VOR routes are generally well aligned to the enroute traffic demand. In most terminal areas the VOR route provides a near optimum direct route from the high or low altitude route structure to the feeder fix for arrival aircraft or from the departure fix to the enroute route structure for departure aircraft.

In order to efficiently meter arrivals the controller should handle arrivals from one or two feeder fixes in a high or medium density terminal area. If more feeder fixes were added the controller would have more difficulty in performing his traffic handling functions. Consequently, both RNAV and radar vector traffic should use the same feeder fix locations. In most terminal areas these points are located approximately 25 nm from the airport or about 20 nm from the perimeter of the terminal area. Independent RNAV routes could have been developed for the 20 nm segment from the perimeter of the terminal area to the feeder fix at some of the seven terminal areas. However, since the VOR routes in this area generally served the direction of traffic demand, little user or controller advantages appeared to be gained by developing the new RNAV route in the terminal area without knowledge of the adjacent enroute RNAV route structure. Consequently, the practice of overlying the VOR routes was determined to be the most advantageous means of developing RNAV arrival routes in the 1972-1977 time period.

A similar case can be made for RNAV departure routes. Current VOR routes in the terminal area generally serve the primary traffic demand directions. In general the most efficient route for the departures is to use these existing routes. An RNAV route that deviates slightly from the VOR route may be slightly shorter but until an enroute RNAV structure is developed, the current VOR departure routes are a very good approximation of the optimum RNAV route for this initial time period.

A comparison of the traffic distribution diagrams which depict the direction of traffic demand and the existing VOR route structures in the terminal transition area indicates that the current routes generally serve the primary traffic demand areas quite well. Most of the seven high and medium density terminal areas studied are presently organized in a spoke or wagon wheel concept. These terminals have designated arrival and departure corridors in the terminal transition area. Usually three to five arrival corridors are used and four or five departure areas are used. The one terminal area where this was not true of the seven that were analyzed was New Orleans which had six arrival areas and

eight departure areas. This terminal was the smallest of the seven. The implication then seems to be that the larger the terminal area in terms of operations the fewer the number of arrival and departure corridors that are used. The underlying principle that is apparent is that as the number of operations in a terminal increases, so does the need exist for a higher degree of airspace organization or structure. Accompanying this structured airspace is a reduction in the amount of controller flexibility. In a terminal area like New York an aircraft will follow essentially the same ground track each time he arrives or departs the terminal area. Radar vectors are given to merge flows and to provide proper separation but the same basic ground track is followed. In a terminal like New Orleans a more dynamic traffic flow situation occurs. The areas established for arrivals or departures may often not be used for a period of time due to the low traffic demand. Through coordination between the controllers handling traffic in these areas, it is often possible for an arrival aircraft to use a departure area that is not in use so that the aircraft may shorten its flight time in entering the terminal area. A similar situation can occur with departure traffic using arrival areas. This type of flexibility should be maintained in RNAV route structures where possible as these procedures can benefit both the controller and the user.

The most complex 1972 terminal design problems occur in the metroplex terminal areas. Of the seven terminal areas analyzed New York, Chicago, San Francisco and Miami are considered metroplex areas. The presence of two or more major airports in these terminal areas generally caused a number of crossing route situations to occur. Often traffic on these crossing routes had to be restricted in altitude so that adequate airspace separation could be maintained. While these altitude restrictions were usually not difficult to implement in a terminal route design, they are costly from a user economic viewpoint and are to be avoided if at all possible. Consequently, there is a trade-off involved in moving the crossing routes on a plan view of the terminal and creating longer routes with no altitude restrictions and in providing the shorter route by utilizing altitude restrictions. In most of the metroplex areas that were analyzed the shorter route with crossing restrictions was used.

In these metroplex areas no difficulty was encountered in developing RNAV routes that overlie the radar vector/VOR routes to the major airports from the primary traffic demand directions. Many altitude restrictions were necessary in the New York and San Francisco terminal areas. Fewer altitude restrictions were necessary in Miami and Chicago. The differences in these terminals is primarily caused by the interaction of the runway orientation, the enroute traffic flow direction, and the proximity of the major airports and the satellite airports. In Chicago and Miami the location of the arrival and departure routes is such that the satellite traffic can operate underneath the traffic to the major airport in the major traffic flow directions. This procedure cannot be applied to all directions of traffic flow at San Francisco and New York.

During the 1972 implementation period holding airspace in the terminal area for RNAV traffic will be at the feeder fixes which is at the same location used by the VOR/radar vector traffic. No difficulty in reserving holding

airspace for arrivals at the feeder fixes was encountered since airspace is already allocated at these locations for holding. No holding areas were considered for departures in the 1972-1977 time period.

The terminal transition area RNAV routes which overlie the radar vector/VOR routes that were developed for the 1972-77 time period were compared to the Task Force octant design concept. Only one terminal area, Chicago, is well aligned to the octant flow pattern. The Miami area is generally aligned in an octant pattern in the high density routes to the north. However, considering the current procedures for the remainder of the airports, the octant concept is not generally followed.

There is definitely a pattern of alternating arrival and departure sectors at the other terminals but the alignment of the sectors and the size of the sectors is based upon traffic demand rather than a specific size and orientation based upon primary runways as recommended by the Task Force.

5.2.1.2 Terminal Maneuvering Area Routes

In conventional terminal area designs at high and medium density terminals the traffic inside of the feeder fixes is handled via the radar vector, altitude restrictions and speed control. Insofar as RNAV route design is concerned in this area, the RNAV routes must overlie or be very close to the radar vector path. The routes over which the aircraft are vectored depend upon the active arrival and departure runways. As the active runways change, so do the radar vector routes change in the terminal maneuvering area.

In the 1972 RNAV designs that were created, the radar routes could be identified and overlying RNAV routes could be established on the vector routes. As the active runways change, the RNAV routes in the terminal maneuvering area must change also.

The effects on terminal maneuvering area routes of a metroplex area and of local terrain were observed in the New York, San Francisco and Denver designs. In New York some parts of the airspace delegated to the Kennedy controllers and the La Guardia controllers change as the active runways change at each airport. This lack of independence is necessary because of the overlapping terminal maneuvering areas of the two airports. The effect of these situations upon RNAV route design is also one of a lack of independence. Each runway configuration at the two airports must be treated as a separate design problem. For example the La Guardia departure traffic from Runway 13 use different routes depending on whether Kennedy is landing on Runway 04R or Runway 22L. During the 22L operations at Kennedy, the La Guardia climbs to the northeast (Whitestone Meadow climb) must be discontinued due to a possible conflict between the La Guardia departures and the Kennedy arrivals. Instead a climb to the southeast (called the Maspeth climb) must be performed. When Kennedy is landing on 04R either climb from La Guardia is possible.

Terrain can have a similar effect upon routes in the terminal maneuvering area. In the San Francisco terminal area, traffic departing the San Jose air-

port to the southeast must stay less than 6-7 miles east of the runway centerline while climbing to about 6,000 feet in order to avoid high terrain. Similar terrain problems exist at Denver. Modification to the Task Force concept for terminal maneuvering area routes can be expected in any terminal area that has high terrain features.

The one other consideration that affected terminal area routes in many of the seven areas was noise abatement climbout procedures. Some areas like Philadelphia and Newark vectored the aircraft over rivers shortly after takeoff in order that the climbout may take place over uninhabited areas. Other airports curtail operations on some runways. This procedure is used at New Orleans. Either noise abatement procedure can affect the number and location of terminal maneuvering area routes and can be easily accomplished by using RNAV routes and procedures.

5.2.1.3 Field Controller Comments

During the briefings that were held at the regions with field controllers in attendance,comments upon the RNAV Task Force terminal design concepts were obtained. In general the controllers found the concept of overlying VOR/radar vector routes to be satisfactory for the 1972-77 time period designs. Several comments concerning the specific location of routes were made at several of the briefings. These comments were discussed in the description of the specific terminal areas in preceding paragraphs.

The primary comment that was voiced by the controllers during the briefing at the regions about the initial 1972-77 terminal designs concerned the depiction of the box pattern in the terminal maneuvering area. Several controllers mentioned that this pattern appeared to show a potential head-to-head confrontation for aircraft at the juncture of the base and final approach leg. It must be noted that the depiction on these maps is intended to show the charted RNAV route with its associated waypoints and altitude restriction points and this does not necessarily coincide with the actual flight path of the aircraft. In particular, at the route turn points the turn anticipation features of the RNAV system or the procedural turn anticipation techniques employed by the pilot will normally produce a turn undershoot such that the aircraft actually fly a rounded 90° corner rather than a square corner as shown on the route maps. This difference in the actual aircraft flight path versus the charted route is shown in Figure 5.68. It can be observed from this diagram that aircraft do not actually intercept the final approach leg at a 90° angle but rather the turn anticipation provides for a gradual intercept of this course.

5.2.2 Validation of the 1972-1977 Design Concept

The validation of the 1972-1977 RNAV terminal design concept had two different aspects. The first was the development of the RNAV route designs for the seven terminal areas. The second aspect of design validation consisted

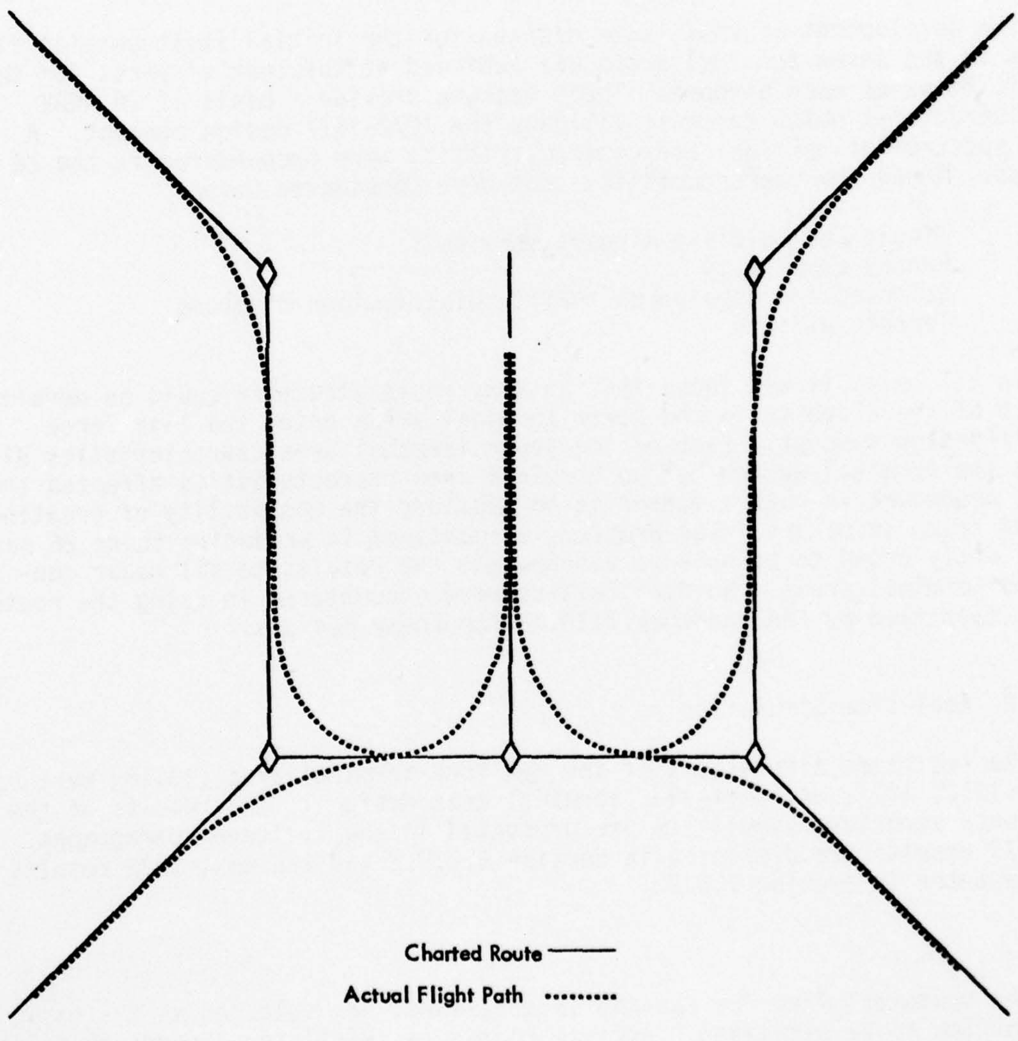


Figure 5.68 Actual Flight Path vs. the Charted Route in the Final Approach Area

of a real time simulation of the 1972 New York Terminal area at NAFEC. The simulation was designed to evaluate the problems of the controller and the user in operating in airspace with various mixes of RNAV and conventional radar vector/VOR traffic.

5.2.2.1 The 1972-1977 RNAV Route Design

The development of RNAV route designs for the initial implemenation time period in the seven terminal areas was achieved at thirteen airports for two traffic flows at each airport. These designs provide a basis of 26 RNAV route structures which serve to validate the 1972-1977 design concept. A broad spectrum of terminal area characteristics were encountered in the 26 designs. Among the characteristics that were considered were:

Single and multiple airport terminals
Runway complexity
Balanced and unbalanced traffic distribution diagrams
Terrain effects

In all cases it was found that an RNAV route structure could be developed at each of the airports in the seven terminal areas using the Task Force 1972-77 design concept. Each of the above terminal area characteristics did affect the terminal design but no terminal area characteristics affected the design procedure in such a manner as to preclude the possibility of creating an RNAV route structure. The problems encountered in producing these 26 designs are sufficiently broad to be able to extrapolate the results to all radar controlled terminal areas. No difficulties were encountered in using the route widths specified by FAA Handbook 7110.18 for these designs.

5.2.2.2 Real Time Simulation

The real time simulations of the New York terminal area [13,18] were based on the 1972, 1977, and post-1982 terminal area designs. The results of the 1972 route structure simulation are presented in the following paragraphs. The 1977 results are presented in Section 6.2.2.2 and the post-1982 results are presented in Section 7.5.5.

The southwest flow for Kennedy International was selected as the basic traffic flow to be simulated. Arrival routes to satellite airports at Islip and Republic were developed as these airports are handled by Kennedy controllers. Departures from Kennedy, Islip, Republic, and southwest bound Newark and La Guardia departures were simulated since JFK departure control positions handle traffic from these airports. Airspace was reserved for operations at these other airports. Only traffic controlled by Kennedy operating positions was used in the analysis of controller activity. The traffic to the other airports was provided to give the Kennedy controllers realistic traffic and workload levels.

In the simulation of the 1972 design the percentage of RNAV aircraft that were simulated varied from 0% to 75% in 25% increments. Five controller teams were used at each RNAV percentage or participation level. A total of 20 one hour data runs were made to form the data base (five controller teams times four RNAV participation levels). The parameters that were measured pertained to controller workload and controller traffic handling techniques. Specific measures of controller workload included the number of radio contacts, the controller radio communications time and the percentage of RNAV clearances broken as shown in Figures 5.69, 5.70 and 5.71. Each of these workload measures shows a significant decrease as the percentage of RNAV traffic increases. The dotted line connecting 75% and 100% values is an extrapolation of the simulation results to 100% RNAV based upon the 0% to 75% RNAV cases. Both the number of radio contacts and the radio communications time parameters descreased by 24% in going from 0% to 100% RNAV traffic. Similarly, the number of RNAV clearances broken for arrivals dropped from 40% to 20% from the 25% RNAV case to the 75% RNAV case. The number of clearances broken for departures did not change as a function of RNAV traffic percentage but stayed at a low value of 7% for all percentage levels. These data summaries indicate a definite trend to less controller workload as the RNAV percentage increases.

The methods used by the controller to handle the aircraft can be broken into three categories; horizontal flight path control, altitude control and speed control. The horizontal flight path control is made up of radar vector instructions for VOR equipped aircraft and RNAV instructions plus any necessary radar vectors for the RNAV equipped aircraft. In Figure 5.72 both the total number of control instructions and the flight path control instructions are shown. The difference between the curves is the number of speed control and altitude control instructions together. A definite decrease in the number of flight path control instructions is depicted in Figure 5.72 while the number of speed and altitude control instructions changed very little. The control instructions that were used to control the flight path of the aircraft are shown in Figure 5.73, 5.74 and 5.75. The number of radar vectors issued dropped significantly as the percentage of RNAV participation increased. Conversely, the number of RNAV instructions increased considerably for both the parallel offset and the direct to way point instruction.

These real time simulation results fully support the conclusion that the controller can effectively control mixed RNAV and conventional traffic in a high density terminal area like New York. In addition, it is apparent that the use of RNAV generally produces some controller workload reduction. Detailed descriptions of the simulation and the results are obtained in Reference 13.

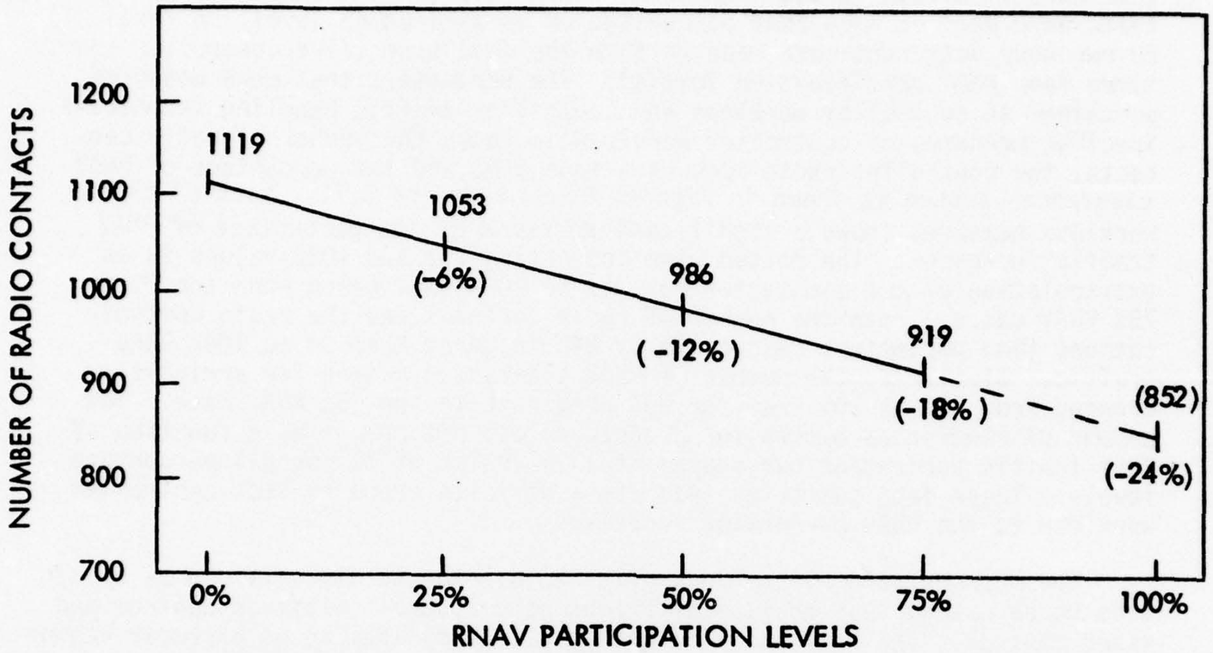


Figure 5.69 Number of Radio Contacts

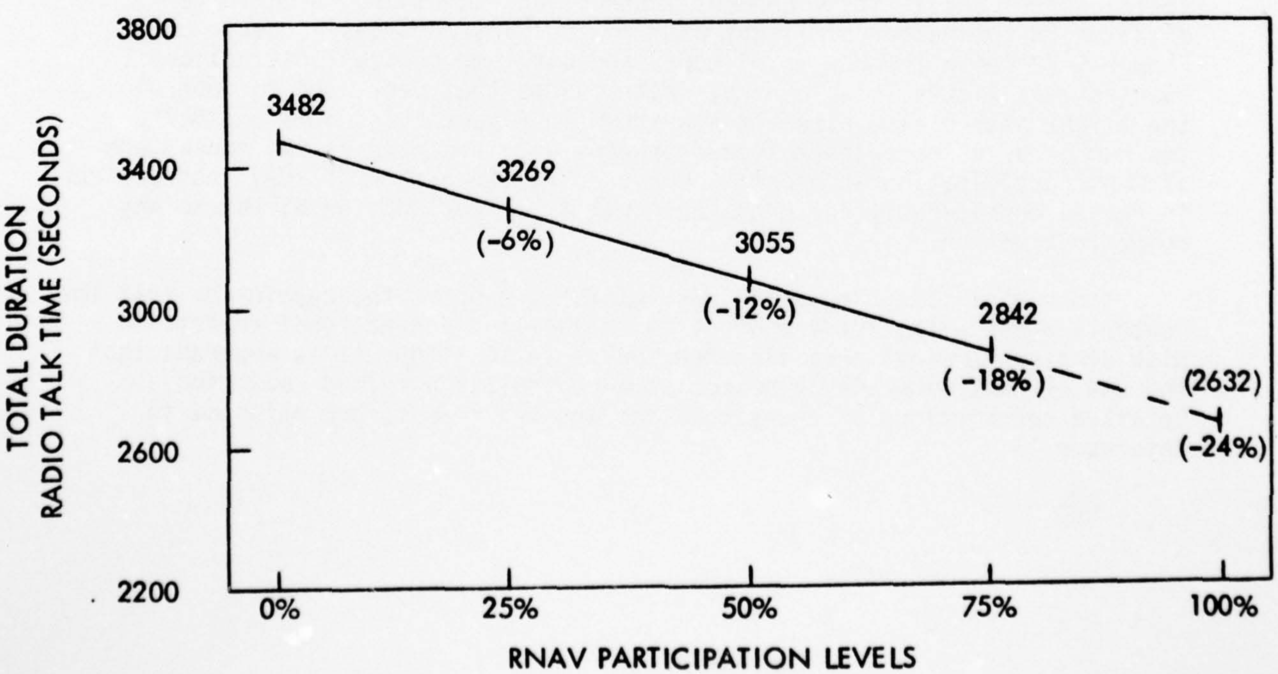


Figure 5.70 Radio Communications Time

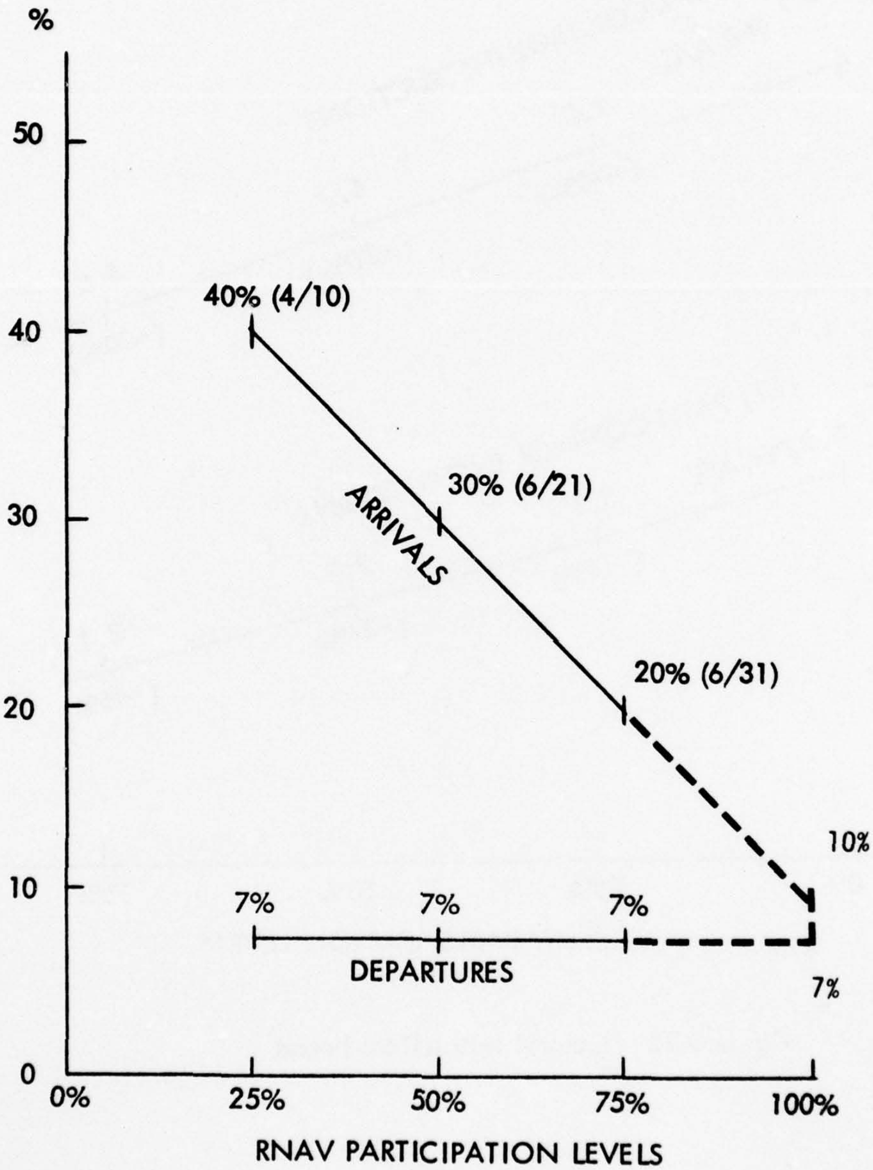


Figure 5.71 Percent RNAV Clearances Broken

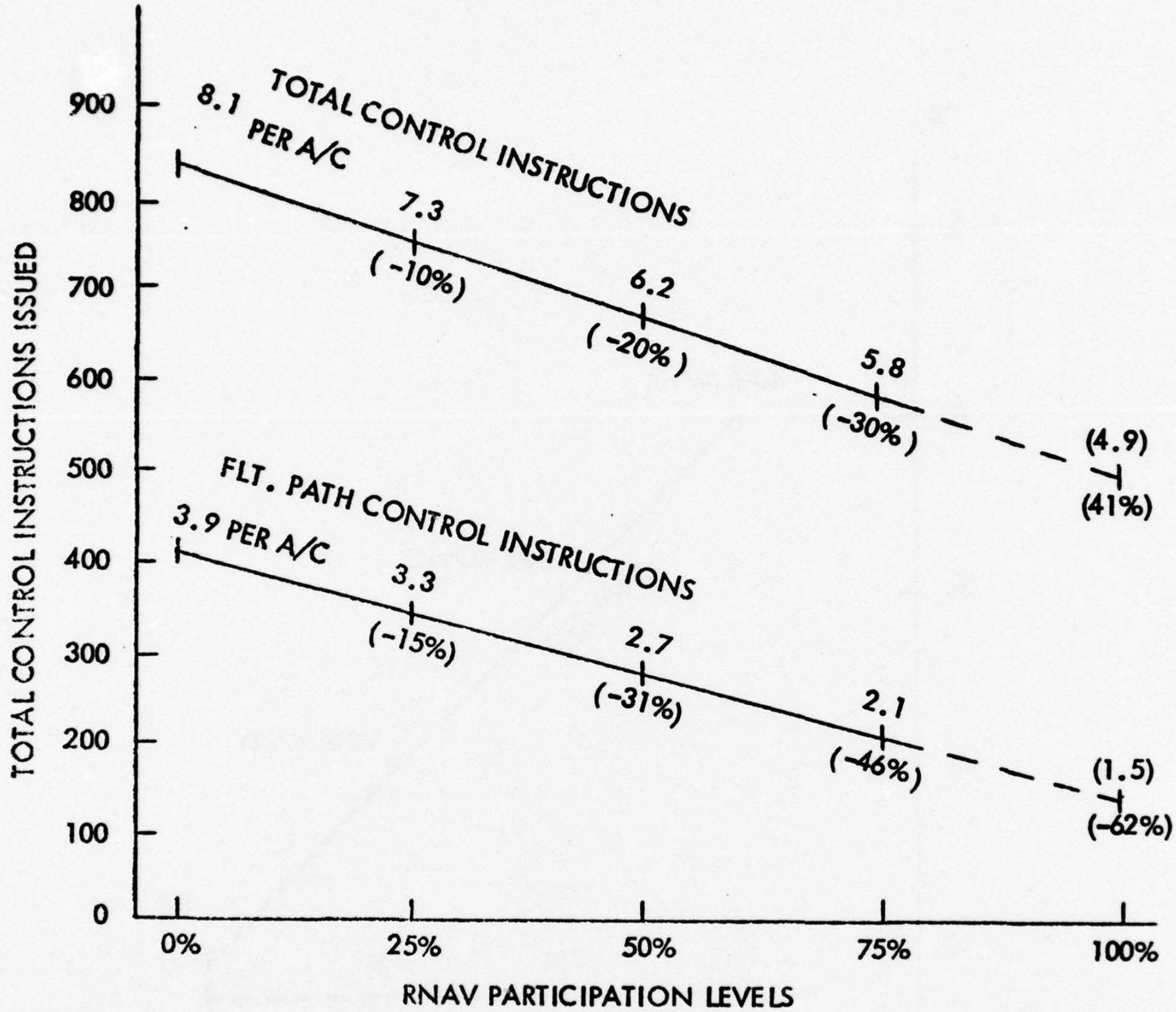


Figure 5.72 Control Instructions Issued

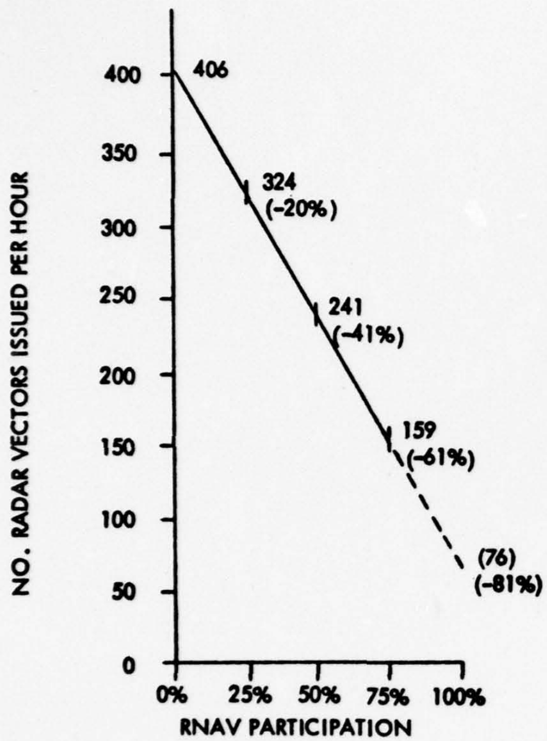


Figure 5.73 Radar Vectors Issued

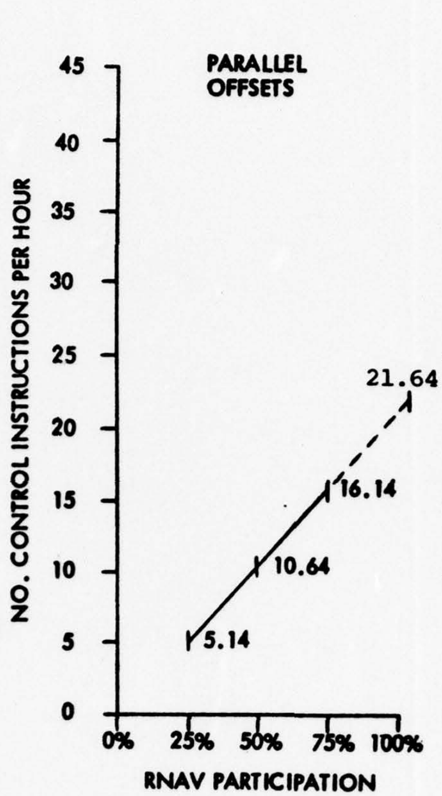


Figure 5.74 Parallel Offsets

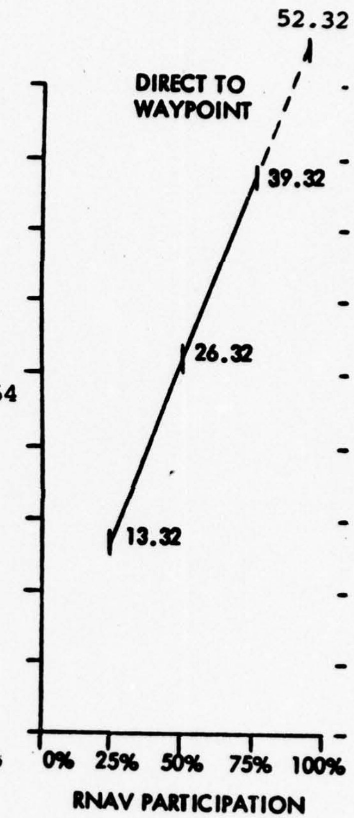


Figure 5.75 Direct to Waypoint

6.0 1977-1982 2D DESIGNS AND ANALYSIS

The 1977-1982 terminal area designs are developed for that phase of the RNAV implementation process when there is an approximately equal mix of RNAV and VOR/radar vector aircraft operating in the terminal area. As the percentage of RNAV equipped aircraft increases, then it is desirable to change the route structure to provide increased economic benefits for the airspace user. Consequently at some point less than 100% RNAV traffic it is desirable to shift to the 100% RNAV design of the post-1982 period in order to achieve the maximum economic benefits for the user. The radar vector/VOR aircraft that desire to use the terminal area must then be radar vectored to the airport or be regulated in some other less than optimum manner.

During this second transition time period it is desirable to develop the route structure in such a manner as to begin to achieve the user benefits that are provided by the post-1982 terminal designs. This can be achieved by patterning the 1977-82 designs as closely as possible to the post-1982 designs. In this manner the economic benefits for the RNAV users can begin to be achieved. The degree to which this can be achieved depends upon the amount that the optimum RNAV design must be compromised to accommodate radar vector/VOR traffic. From a route design standpoint this implementation phase provides a more severe constraint upon a terminal route structure than does either the 1972-77 designs or the post-1982 designs. The constraints are basically that the RNAV terminal area routes be patterned as closely as possible to the post-1982 design concept in order for the RNAV user to obtain maximum user economic benefits. On the other hand, during the initial implementation of the 1977-82 design phase many users would be using VOR and radar vectors to navigate within the terminal area airspace. Consequently compatible sets of VOR radar vector routes and RNAV routes must be developed in this time period.

In order to provide a 1977-82 design that could be easily transformed into the post-1982 design and also afford RNAV aircraft with routes which could provide user benefits, the 1977-82 design was patterned after the post-1982 design. This meant that the traffic flow patterns in the terminal transition area and the terminal maneuvering area for the post-1982 time period had to be developed before the 1977-82 design work could begin. The first step in this process consisted of selecting the orientation and the location of the post-1982 octant configuration that was discussed in Section 3. The major aspects of the post-1982 design procedure were completed before the 1977-82 design process was started. This procedure provided assurance that the 1977-82 terminal designs would be very compatible with the post-1982 designs.

Once the post 1982 route structures had been developed the 1977-1982 design procedure began by overlying VOR/radar vector routes on the RNAV routes. This is the inverse of the 1972-1977 design procedure. In the terminal maneuvering area a radar vector environment was assumed to exist for the conventional aircraft. In the terminal transition area VOR navigation was assumed. The VOR locations were assumed to remain as they are at the present time and no new VORs were assumed in the development of the VOR routes. All VOR routes were designed to follow inbound or outbound VOR radials. Specific locations

were developed using VOR intersections on the VOR routes. DME was not assumed to be necessary. The range of the VOR stations was assumed to be the frequency protection limits of 40 nm for a "L" facility and 130 nm for a "H" facility. Once the VOR route constraints has been added to the existing post-1982 RNAV route structure, necessary moves in the RNAV route structure were made in order to make the VOR/vector route and the RNAV routes compatible.

At most of the seven terminal areas that were considered in the design effort the feeder fix for arrivals was a point of special significance. It generally marked the point at which current VOR routes from a given direction converge to a single flow. In addition, it was often the final point along the arrival path in which aircraft could be put into a holding pattern at several altitude levels. Consequently, in the current airspace environment the terms holding fix and feeder fix can often be used interchangeably. The corresponding terminal area point in the Task Force terminal area model is the low altitude arrival waypoint. In a non-automated metering and spacing environment the holding fix, the feeder fix and the low altitude arrival waypoint could often be located at a single point for aircraft arriving from the same general direction. In an automated metering and spacing environment the need for the holding airspace in the terminal area is reduced considerably. As a result, the term holding fix is generally invalid as a description for the feeder fix or the low altitude arrival waypoint in a metering and spacing environment. However, there often may be a close correspondence between the terms feeder fix and low altitude arrival waypoint.

In the initial 1977-1982 terminal design effort holding airspace was not considered. The assumption was made that automated metering and spacing would be in effect at most of these seven terminals and thus terminal holding would not be necessary. This same assumption was made by the Task Force in their 1977 and 1982 time period recommendation. Also, based on Task Force recommendations, terminal route widths of ±1.5 nm were assumed in the 1977 designs. However, after the designs had been completed an analysis was made on several of the route structures to ascertain what changes would occur in the 1977-1982 route structures if holding areas were necessary and if ±2.0 nm route widths were used. These effects are discussed in the sections that describe the terminal designs.

6.1 2D RNAV DESIGNS

The following sections describe the 1977 terminal area designs that were developed for the seven terminal areas. Completed route structures for the same two flow configurations chosen in Section 5 are shown for all of the terminal areas. Section 7 describes the 1982 designs that were used as a basis for the 1977 designs and may be referred to for clarification of the 1977 design. The appropriate parts of Section 5 many also be useful as an aid in relating enroute traffic flow to the octant pattern and the traffic patterns in the terminal maneuvering area.

No modified 1977 designs were made subsequent to the terminal area briefing trips. It was felt that the 1977 RNAV route design procedures for the terminal areas had been established and validated with the initial design

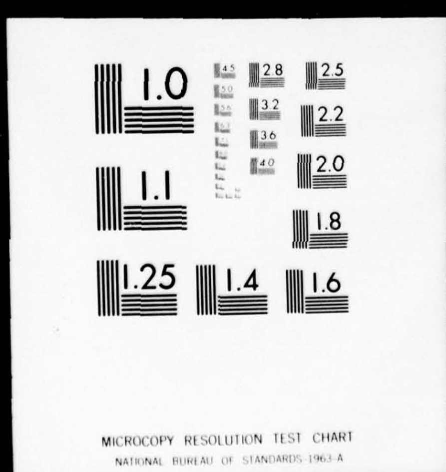
AD-A037 022 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
TERMINAL AREA DESIGN - ANALYSIS AND VALIDATION OF RNAV TASK FOR--ETC(U)
OCT 75 E D MCCONKEY , W H CLARK DOT-FA72WA-3098

UNCLASSIFIED FAA-RD-76-194 NL

3 OF 6
ADA037022

3 OF 6

ADA037022



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

effort. The primary use of the designs that were created after the terminal area briefings was for use in the terminal area user benefits analysis. Consequently, it was determined that further 1977 route design efforts were not necessary for the purposes of the study.

6.1.1 New Orleans

6.1.1.1 The 1977 New Orleans Terminal Ar Design

In order to develop the 1977 New Orl ns Terminal Area Design, the airspace surrounding New Orleans Internationa irp t was first divided into eight 45° sectors or octants. The center of octant pattern was located at the MSY airport reference point at

Latitude N29° 59.5'
Longitude W090° 15.3'

The centerline of the West Departure Octant was aligned parallel to the Runway 10 extended centerline which has a magnetic bearing of 100° and a true bearing of 106°. The extent of the terminal area design went out to 45 nm from the airport reference point. Circles were also drawn at 15 nm and 28 nm from the airport reference point to mark the desired location of the low altitude departure fix and the low altitude arrival fix respectively. (The 28 nm circle was used to keep arriving aircraft at least 33 flight path miles from the closest runway at the low altitude arrival waypoint. This distance also corresponds well with currently used feeder fixes). Traffic flow patterns were then established from these fixes based upon the location of current VOR facilities and by keeping all routes within the specified arrival or departure octant. In some cases, it was necessary to move the arrival and departue fix from its octant centerline location to keep the route or routes within the proper octant and to use the existing navigation facilities. Inside of the arrival and departure fixes radar vectors would be required to keep conventionally equipped VOR aircraft on course. However, RNAV equipped aircraft could fly the arrival and departure patterns utilizing their RNAV computers with waypoints established at appropriate turn points and other operationally significant locations.

Arriving Traffic - 1977

The 1977 New Orleans routes for low and high altitude aircraft are shown in Figures 6.1 and 6.2. Feeder fix locations are determined by the location of the low altitude arrival waypoint described in Section 3. In the vicinity of the airport, traffic arriving from the downwind side of the airport follow a conventional downwind, base and final approach course on each side of the airport. Aircraft arriving at the upwind side of the airport proceed from the feeder fix to intercept the localizer about 10 nm from the runway threshold. At the outer edge of the terminal design the routes are designed to service the traffic depicted in the low and high altitude traffic distribution diagrams by using VORTACs at their present locations. In all arrival octants a satisfactory flow pattern was achieved using this procedure.

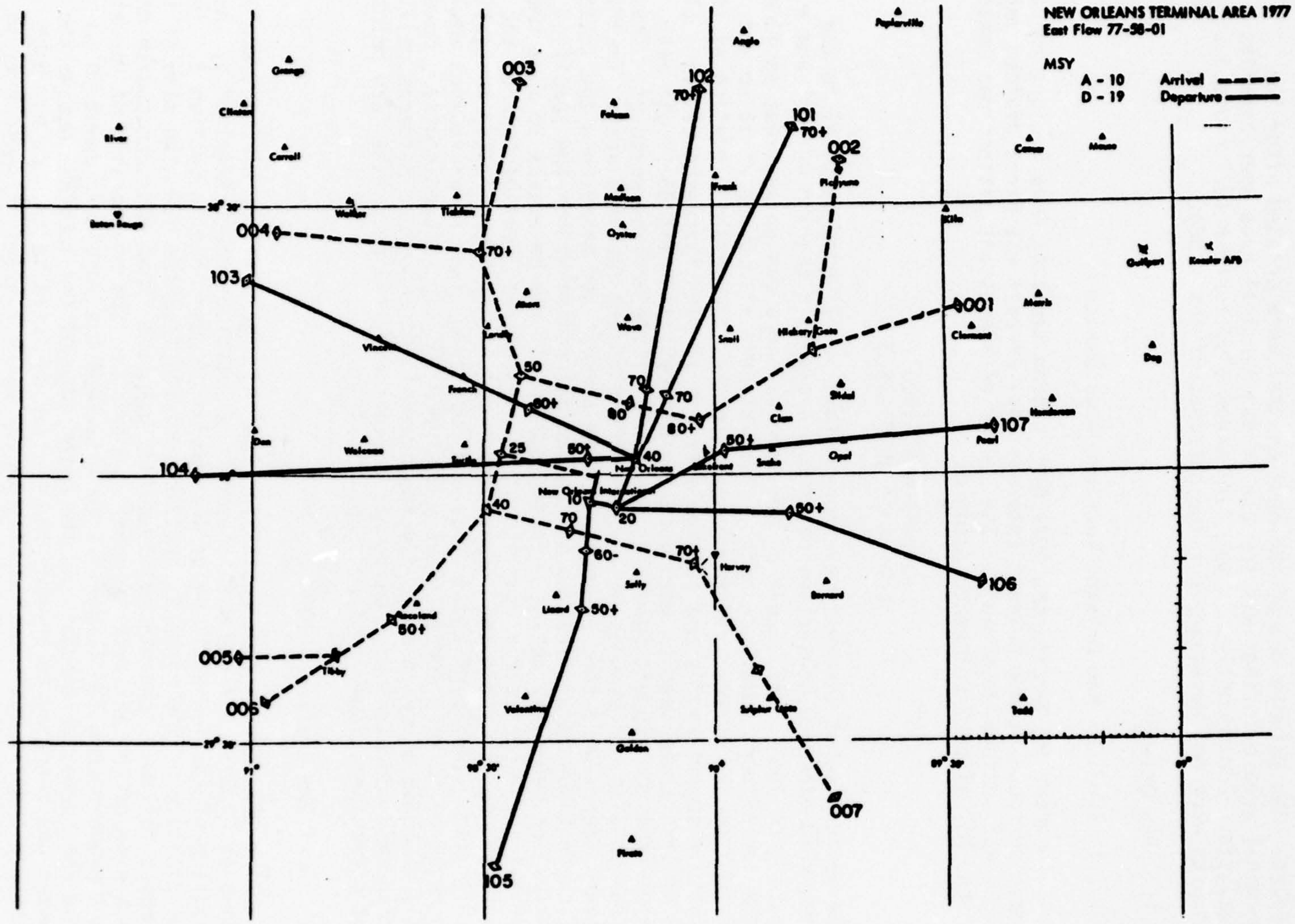


Figure 6.1 New Orleans Terminal Area-1977 Routes, East Flow

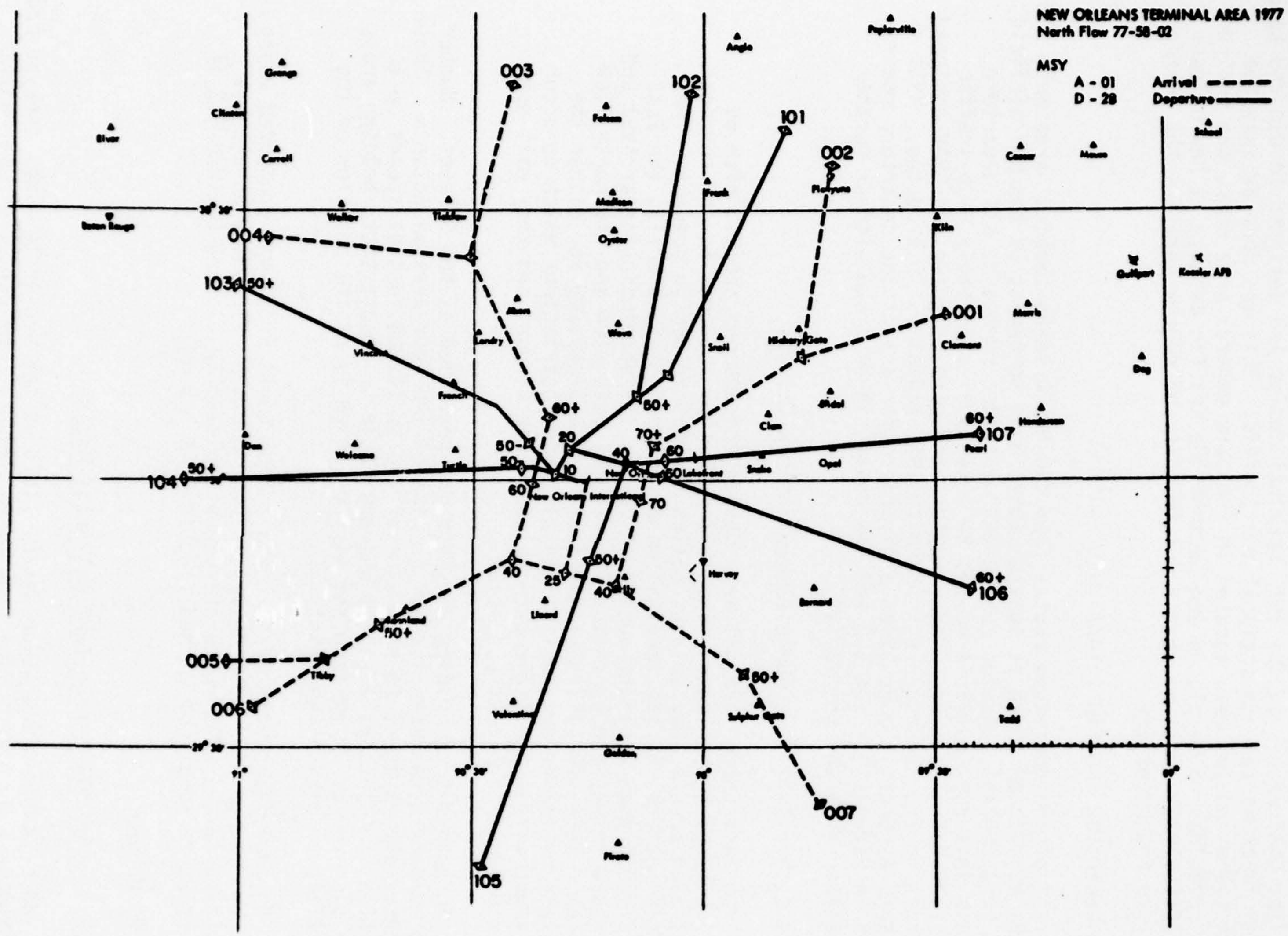


Figure 6.2 New Orleans Terminal Area-1977 Routes, North Flow

The RNAV routes in the 1977 terminal design are designed to use the same ground track as the conventional VOR traffic. This was done because the conventional routes were located in the same general area where the desired RNAV route was to be placed and because the traffic density at New Orleans is sufficiently small so that a multiplicity of routes entering the terminal area are not necessary.

Departing Traffic - 1977

All of the departure routes from the New Orleans terminal area make use of the MSY VORTAC which is located about 5 nm northeast of the MSY airfield. From this central location convenient departure routes to all departure octants including multiple routes to octants of moderately high traffic density can be designed. Radar vectors are used to guide non-RNAV equipped aircraft to the departure fix where the MSY radial is intercepted. RNAV equipped aircraft can be given a clearance for any of the departure routes shown in Figures 6.1 and 6.2 and the route can be flown without further assistance from the controller.

6.1.1.2 The 1977 Task Force Concept at New Orleans

The Task Force terminal area design concept was applied with no difficulty at New Orleans. The 1977-1982 flow patterns in the terminal transition area at New Orleans follow the octant design concept. The traffic patterns in the terminal maneuvering area also follow the Task Force model with a slight modification for the perpendicular arrival and departure runway configuration in both the east flow and the north flow designs. Very few altitude restrictions are necessary for either the arrivals or the departures. Those altitude restrictions which do occur are found within 20 flight path miles of the airport and they will not produce large user cost penalties.

An analysis of holding airspace was performed at New Orleans. Number 10 size holding areas were located in each of the four arrival octants. These patterns are designed to hold aircraft up to 14,000 feet at speeds up to 230 KIAS. Sufficient airspace was available to locate these holding areas at a distance of 28 nm from the airport which is at the position of the low altitude arrival waypoint.

An analysis of the effect of a ± 2 nm route width was conducted using the New Orleans 1977-1982 design. There would be virtually no changes necessary in the RNAV route structure depicted in Figures 6.1 and 6.2 if ± 2 nm route widths were used instead of ± 1.5 nm.

6.1.2 Denver

6.1.2.1 The 1977 Denver Terminal Areas Design

An octant configuration was overlaid on the Denver terminal area in order to establish an octant flow concept at Denver. The center of the octant pattern was located near the center of the 08R-26L runway. This runway was selected as the principal IFR runway because runway 26L is the active runway in the preferred west flow configuration.

The traffic flow patterns in the 1977 Denver terminal area design were altered considerably from the 1972 terminal configuration. The primary change in the flow pattern is to modify those arrival and departure routes which are in conflict with the octant flow concept. Such changes require that some arrival fixes become departure fixes (e.g., Byers and Platte) while other fixes remain arrival fixes (e.g., Lyons and Shawnee). Similarly, the departure routes in the 1972 design become arrival areas in the 1977 design in the northeast and southeast arrival octants. (Figures 6.3 and 6.4).

The traffic flow patterns in the terminal maneuvering area of the airport have also been modified considerably from the 1972 design. Slight changes have been made in the west flow configuration to relieve the area about the Denver VORTAC of some of the traffic congestion. This was accomplished by extending the right base leg to about 11 nm to direct the arriving traffic north of the east bound departures. Also, in the east flow configuration both the right and left base leg were extended to 10 nm to permit departing traffic to the west on routes 102 and 302 to gain sufficient altitude to clear the base legs. These base leg extensions plus the alignment of the arrivals to the arrival octants has removed the necessity to route westbound departures up to the north in the 1977 design, thus shortening their path length over that of the 1972 design.

In the 1977 design, departures were allowed to top arrivals wherever possible. Due to the high altitude of Denver, a conservative climb gradient of 300 feet/nautical mile or less was used as a guide to the aircraft's performance capabilities. Aircraft not able to achieve this rate of ascent would be tunneled under the arrivals as necessary. This procedure should not be required often, as most routes in the 1977 design require considerably less than a 300 ft/nm gradient. The enroute connecting routes for the conventional and RNAV routes at Denver are shown in Table 6.1.

6.1.2.2 The 1977 Task Force Concept at Denver

The 1977 Denver terminal area design conforms quite closely to the Task Force octant concept. Some deviations are made in the terminal transition area in order to permit VOR equipped aircraft to stay on VOR radials located in the Denver area. The Denver design was one of the first of the seven terminal designs to be developed. Some of the latter 1977 design concepts departed from the Denver design technique in order to produce a slightly more structured or organized airspace. This is particularly evident in the arrival areas. RNAV and VOR traffic arriving over Lyons to the northwest and Kiowa to the southeast are funneled over a common feeder fix. Traffic over Shawnee to the southwest and in the northeast octant were permitted to come inside of the feeder fix without merging. In the 1977 design philosophy that was developed in the later terminal designs, arrival routes were merged at the feeder fix (low altitude arrival waypoint).

Traffic flow patterns in the terminal maneuvering area are in close agreement with the Task Force model in the east flow configuration. In the west flow configuration the north downwind leg was moved five miles further north from its nominal position in order to accommodate departures on Runway 35. This concept of traffic flow in the terminal maneuvering area for

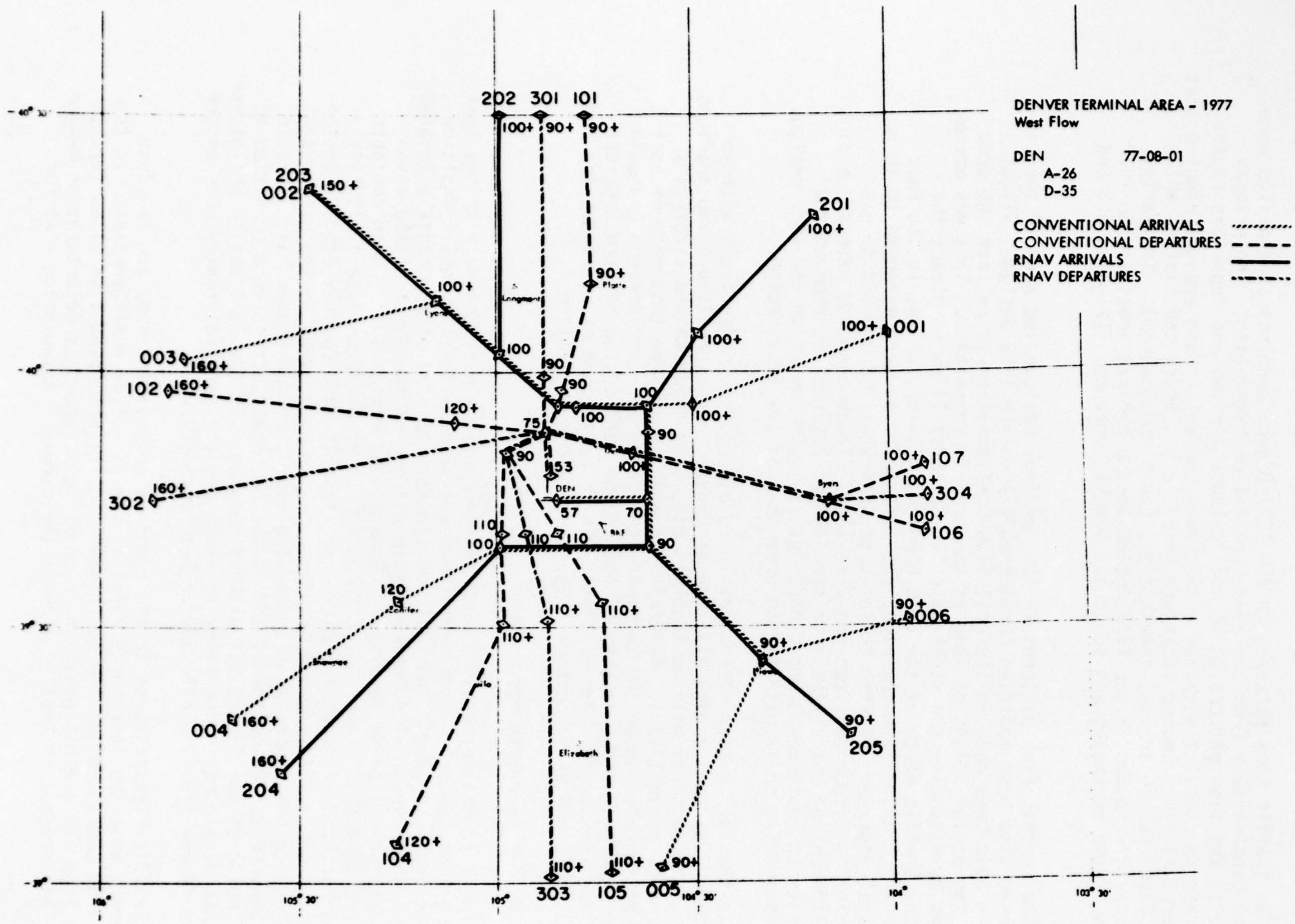


Figure 6.3 Denver Terminal Area-1977 Routes, West Flow

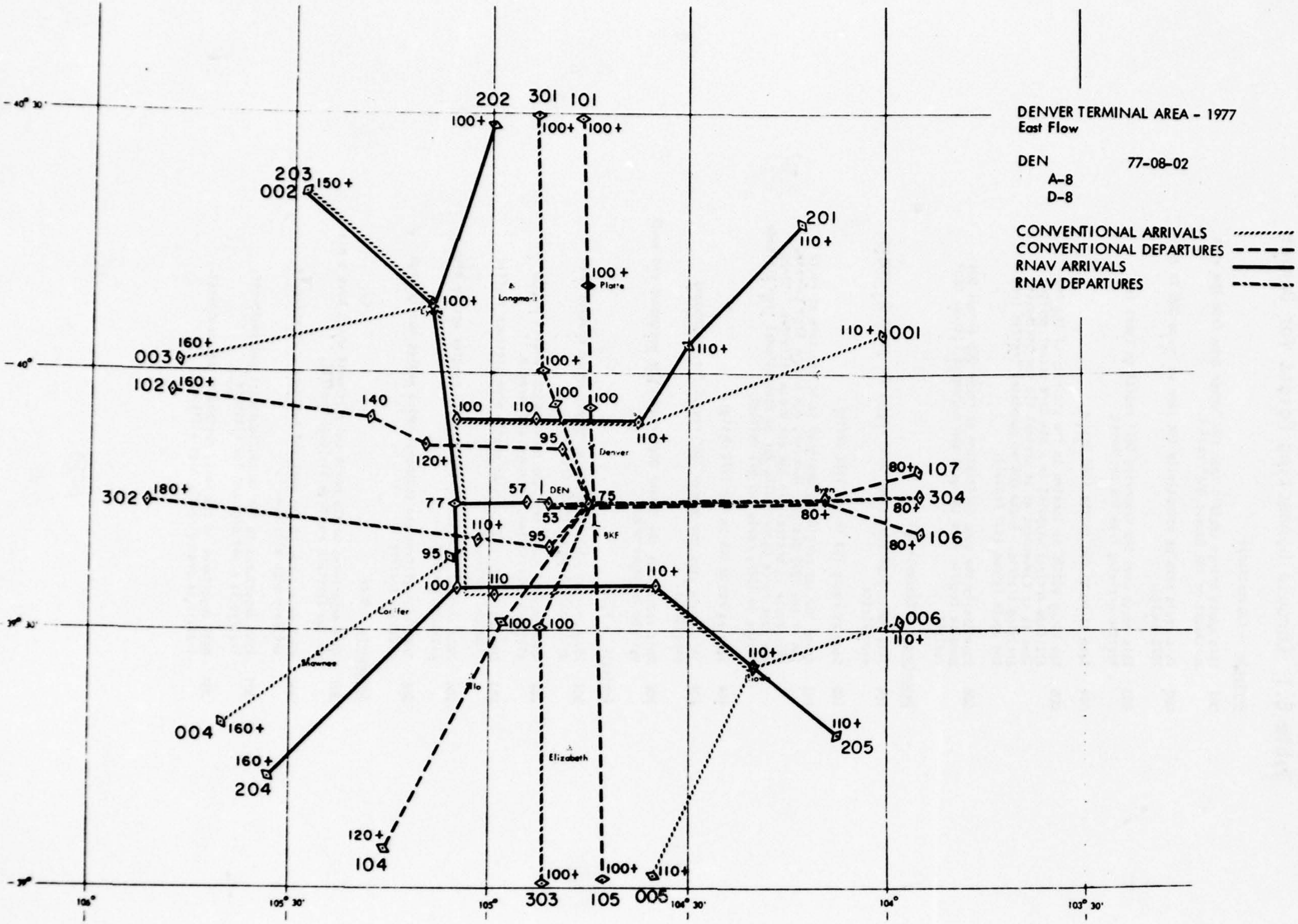


Figure 6.4 Denver Terminal Area-1977 Routes, East Flow

Table 6.1 Enroute Connecting Points for Denver

Arrivals - Conventional

001 This route brings traffic into the Denver area from the east northeast on the Denver 054° radial.

002 This route remains essentially the same as route 005 in the 1972 design.

003 This route uses the Kremmling 067° radial to Lyons for traffic arriving from the northwest.

004 Same as route 006 in the 1972 design.

005 The Kiowa VORTAC is located in the vicinity of the low altitude arrival waypoint in a standard octant design. Thus it is convenient as an arrival fix for southeast arriving traffic. Route 005 accommodates traffic from the south (Kiowa 193° radial).

006 Essentially the same description as route 005 except 006 handles traffic from the east and southeast. (Kiowa 060° radial).

Departures - Conventional

101 This route uses the Denver 346° radial for north departures over Platte.

102 Same as route 103 in the 1972 design.

103 Route 103 was originally designed to be the same as route 104 in the 1972 design. However, due to the high terrain, this route is entirely in the Jet Route altitudes. Since the Task Force Report calls for no conventional high altitude routes in 1977, route 103 was deleted.

104 Same as route 105 in the 1972 design.

105 This route uses the Denver 166° radial for southbound departures.

106 This route uses the Denver 090° radial for eastbound and south east bound departures.

Arrivals - RNAV

201 RNAV arrival route from the northeast which handles predominantly high altitude traffic.

202 RNAV arrival route from the north which handles mostly low altitude traffic from Cheyenne and Laramie.

203 Overlies route 002. handles mostly high altitude traffic from the northwest.

204 RNAV arrival from the southwest which handles mostly high altitude traffic.

205 RNAV arrival from the southeast which andles mostly high altitude traffic.

Departures - RNAV

301 RNAV departures to the north and northwest which have a mix of low altitude and high altitude traffic.

302 RNAV departures to the west and southwest. Traffic is entirely high altitude.

303 RNAV departures to the south, southeast and southwest. Traffic is mixed high and low altitude.

304 RNAV departures to the east, northeast, and southeast. Traffic is predominantly high altitude.

perpendicular runways was adjusted somewhat in subsequent designs. The flow patterns at New Orleans described in Section 6.1.1.1 depict the later design techniques in which the downwind leg is not moved away from the airport. The departures from the upwind direction (e.g., routes 107, 304 and 106) make a climbing 270° turn in the New Orleans concept rather than a sharp 100° turn as shown in Figure 6.3.

Very few altitude restrictions of long duration are necessary in the 1977 Denver designs. Most altitude restrictions are removed once an aircraft is 20 flight path miles from the airport.

Sufficient airspace exists at Denver for holding areas at the low altitude arrivals waypoints at Lyons, Kiowa, Shawnee and the unnamed location to the northeast. Route widths of ± 2.0 nm would not create any necessary major changes in the 1977 Denver terminal design.

6.1.3 Philadelphia

6.1.3.1 The 1977 Philadelphia Terminal Area Design

An octant pattern was overlaid on the Philadelphia terminal area. The octant was centered at the Philadelphia airport reference point at N39° 52.5', W075° 14.3'. The octant was aligned with the runway 09-27 pair which are used for all of the Philadelphia turbojet operations.

The traffic flow in the Philadelphia terminal area in the 1977 design is essentially identical to the 1972 design with few major exceptions. The Yardley-Princeton departure route to the northeast has been deleted and the Turner arrival has been moved south over Yardley. This can be seen in both the east flow and west flow configuration in Figures 6.5 and 6.6. This design change was made to align the traffic flow in the northeast octant with the flow patterns described in the Task Force Report (Section IV) and in Section 3 of this report. The deletion of the Yardley-Princeton route places a greater demand upon routes 101 and 301 to carry the New York-Newark tower enroute traffic. (Note that although the routes are the same as the 1972 design, most route numbers have changed).

With the modifications described in the above paragraph, the Philadelphia terminal area has flow patterns which are in general agreement with the octant flow concept. The RNAV routes are still somewhat less than optimum in their design, however, because they are still somewhat constrained by the conventional arrival and departure routes.

6.1.3.2 The 1977 Task Force Concept at Philadelphia

The incorporation of the octant flow concept for the 1977 terminal routes at Philadelphia was accomplished by slightly modifying the 1972 Philadelphia terminal design. Philadelphia was one of the few terminals in which this 1977 design technique was possible because most other terminals had flow patterns which were in conflict with the octant concept.

Traffic in the terminal maneuvering area at Philadelphia flows slightly different than the Task Force model pattern. A slight left turn is used by

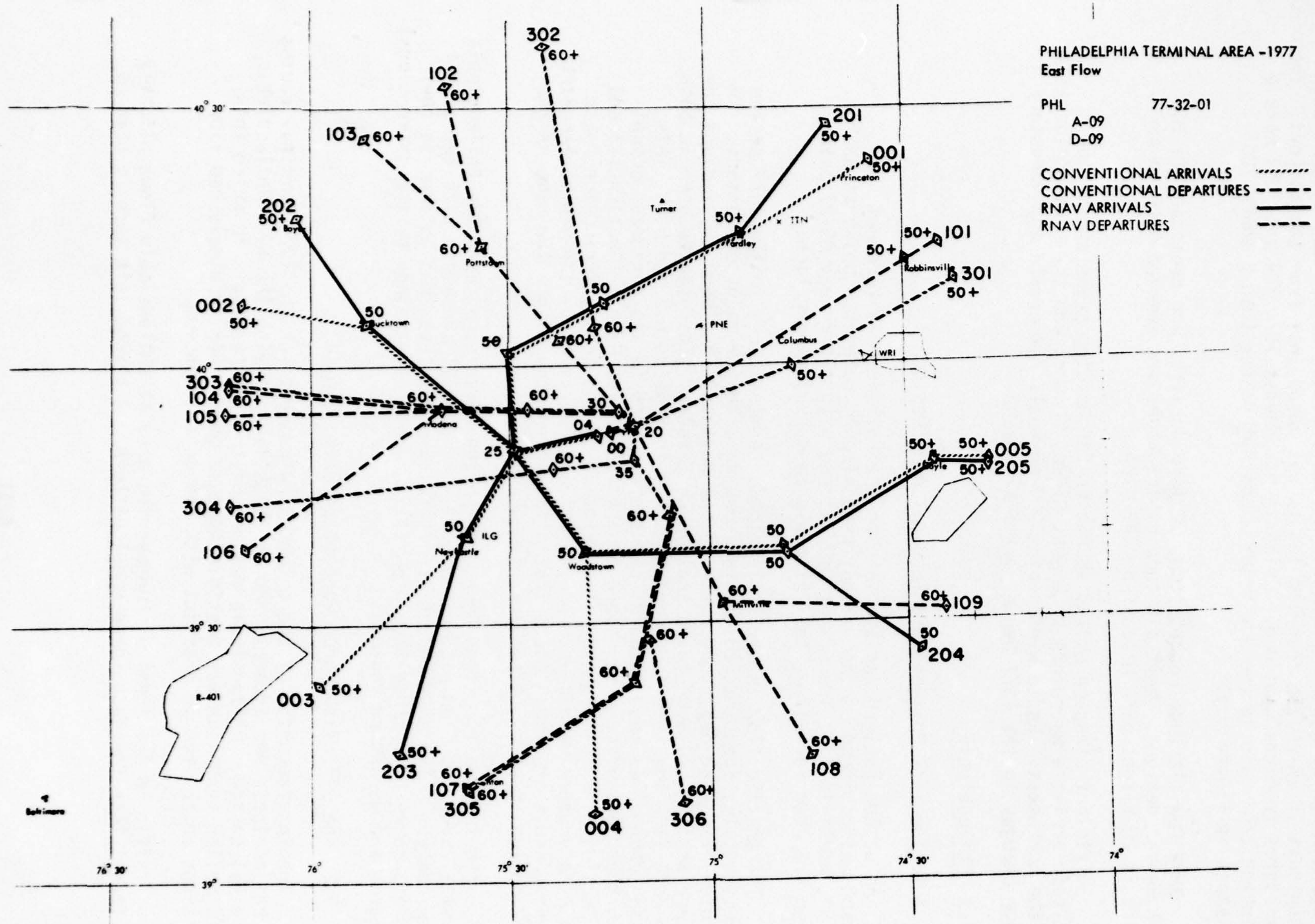


Figure 6.5 Philadelphia Terminal Area -1977 Routes, East Flow

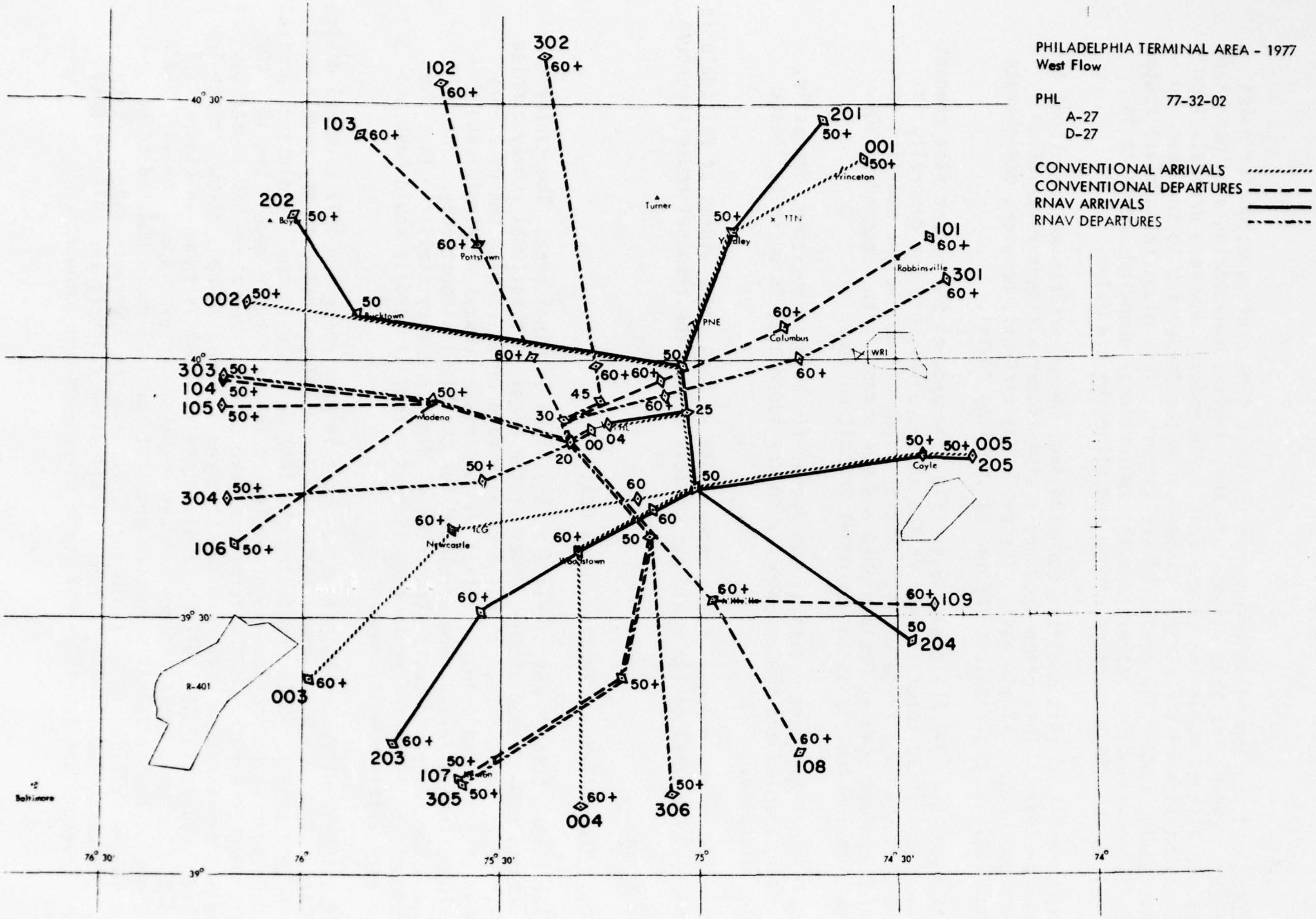


Figure 6.6 Philadelphia Terminal Area - 1977 Routes, West Flow

westbound and southbound departures in the west flow configuration for noise abatement. Except for this slight turn the terminal maneuvering area departure routes are aligned according to the Task Force model. However, arrivals from the downwind side of the airport proceed from the feeder fix to the base leg without coming toward the center of the airport. This gives the arrival routes a modified downwind leg rather than the conventional downwind leg which is parallel to the final approach course and offset by six miles.

As a result of this modified downwind leg, the departures are permitted to top the arrivals. This often produces a significant altitude restriction penalty on the arrival aircraft. The departure aircraft, however, can operate without altitude restrictions imposed by crossing routes.

Although the 1977 Philadelphia traffic flow matches the octant flow concept the location of the terminal area routes and waypoints are not generally in accord with the Task Force model. This is primarily due to the modified downwind leg concept used at Philadelphia and the necessity to accommodate VOR aircraft on VOR radials in the terminal transition area.

Sufficient airspace exists at the feeder fix points, Bucktown, Newcastle, Woodstown, Yardley and the unnamed fix to the southeast, in which to locate holding airspace.

The use of ±2 nm route widths rather than ±1.5 nm route widths at Philadelphia in the 1977 terminal design would not greatly affect the terminal route structure.

6.1.4 Miami

6.1.4.1 The 1977 Miami Terminal Area Design

The octant pattern was overlaid on the Miami Terminal area. The center of the octants was located at the center of the Miami International runway complex at N25° 47.6' and W080° 17.2'. The octants were oriented with the 09-27 R/L runways that are the primary arrival and departure runways at Miami. Route structures for 1977-1982 were developed for the Miami airport only. The 1977-1982 and the post-1982 route structures at Miami are very similar. Thus the development of 1977-1982 route structures for Fort Lauderdale would have produced very little new information.

A slightly different technique was used in developing the 1977 terminal design at Miami. The 1982 Miami route structure was developed prior to any development of the 1977 design. Upon completing the 1982 design with the low altitude arrival and departure waypoints located according to the Task Force model, the 1977 VOR routes were constructed. The technique used to construct these VOR routes was to select radials from Miami and Key Biscayne VORTAC that pass through these low altitude waypoints. The 1977 route structure at Miami is shown in Figures 6.7 and 6.8. The only modification that was necessary in overlaying the 1977 VOR structure on the 1982 RNAV structure was that arrival route 204 had to be deleted in the 1977 design to avoid conflicts with the VOR route and departure route 307 was moved slightly north. In all other respects the 1977 VOR/RNAV route structure and the 1982 RNAV route structures are compatible.

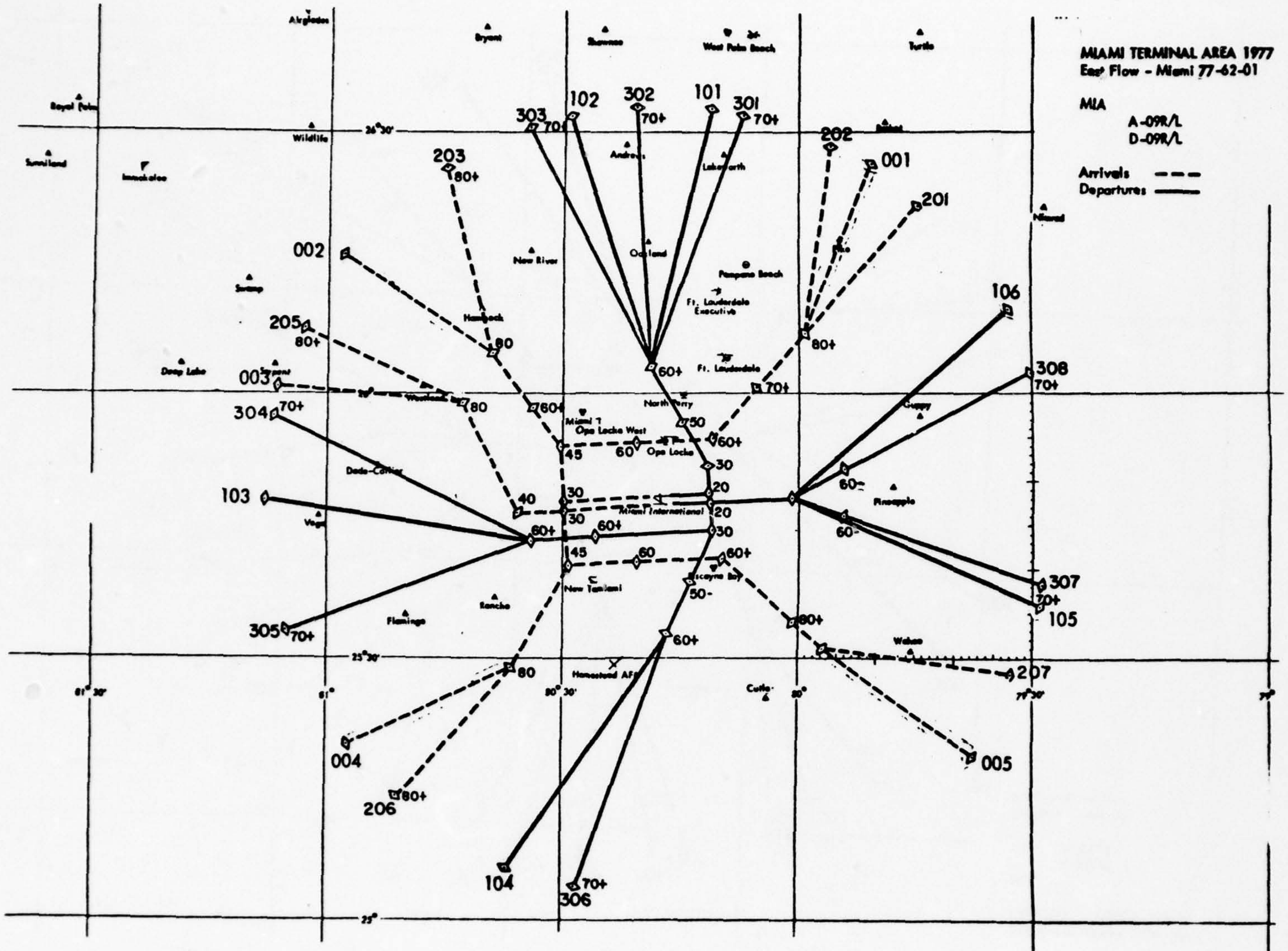


Figure 6.7 Miami Terminal Area - 1977 Routes, East Flow

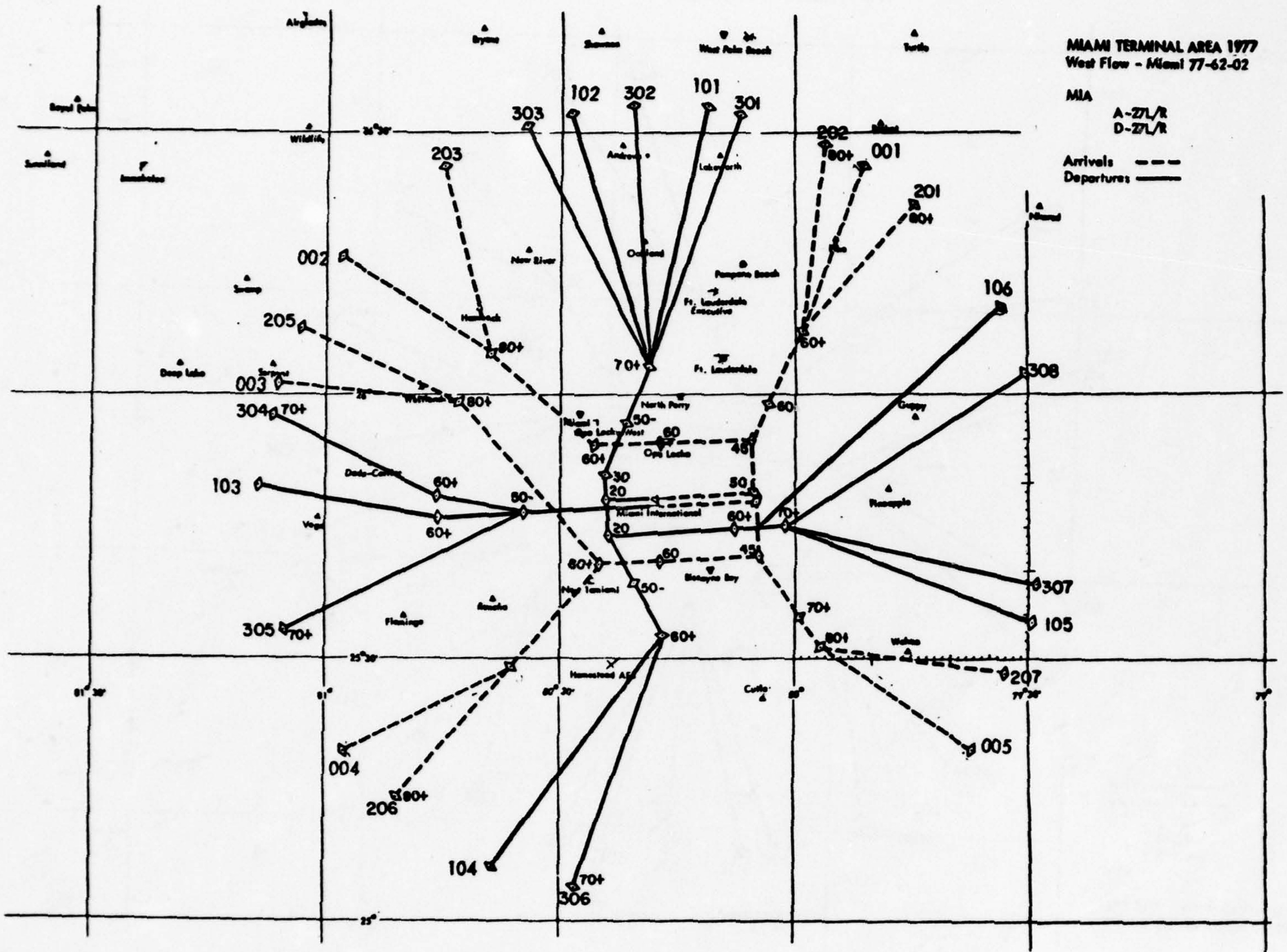


Figure 6.8 Miami Terminal Area - 1977 Routes, West Flow

6.1.4.2 The 1977 Task Force Concept at Miami

The 1977 Miami design is generally compatible with the Task Force model. Some extension to the Task Force model was made to provide arrival and departure routes to both of the parallel runways. A slight modification was made in the terminal transition area to permit the use of dual feeder fixes in the northwest arrival octant to permit independent operations to Runways 09R and 09L. No difficulty was encountered in making this adjustment to the Task Force model.

Routes in the terminal maneuvering area are patterned after the Task Force model. The conventional downwind, base and final approach legs are used for arrivals in the terminal maneuvering area. Arrivals are kept at high altitudes in the vicinity of the airport and departures tunnel underneath with very little altitude restriction penalty.

Holding patterns were located at the low altitude arrival waypoints to see if sufficient airspace was available for arrival holding within the terminal area. No difficulty was encountered in putting number 10 patterns in the arrival octants. Even on the northwest arrival octant, two holding airspace areas were located without overlapping.

If two mile route widths were used at Miami in the 1977 design, the downwind leg to the south of the airport and the departure routes to the downwind side of the airports would both have to be moved slightly south to provide 4 nm spacing between the routes. Other than this minor change there would be no differences in the route design in using 1.5 nm or 2.0 nm route widths.

6.1.5 San Francisco

6.1.5.1 The 1977 San Francisco Terminal Area Design

An octant pattern was overlaid on the San Francisco terminal area. The pattern was centered at a location between the three major airports of San Francisco, Oakland and San Jose. The coordinates of the center were located at N37° 37.1' and W122° 07.4'. From this location a 45 nm circle enclosed all of the present feeder fix locations in the San Francisco terminal area. The octant was oriented with San Francisco Runways 28 R/L which are the landing runways in use during the preferred flow operations. Route structures for 1977-1982 were developed for the San Francisco airport only. The 1977-1982 and the post-1982 route structures at San Francisco are very similar. Thus the development of 1977-1982 route structures at Oakland and San Jose would have produced very little new information.

The use of a 45 nm circle in this metroplex area to define the extent of the terminal area departs somewhat from the Task Force recommended procedure of enclosing all major airports in the terminal with a 45 nm circle

and then enclosing all of the 45 nm circles with one large circle. This large circle concept was found to be impractical in congested areas like the Northeast Corridor where many terminal areas would overlap if this procedure were strictly applied. The procedure which was adopted was to use a 45 nm circle centered on the location of the current feeder fixes to the major airports. If a 45 nm circle did not enclose the feeder fixes then the radius of the circle was increased until the points were enclosed.

The route structure development of San Francisco proceeded in a manner similar to that of Miami. The entire 1982 time period route structure was developed prior to any development of a 1977 time period route structure. After the 1982 RNAV route structure was developed, the 1977 VOR routes were constructed using the existing VOR locations and the 1982 RNAV feeder fix locations at the low altitude arrival waypoint. Figures 6.9 and 6.10 depict the 1977 VOR routes overlaid on the 1982 RNAV routes. The two route structures are generally compatible except for routes 303 and 304 in the southeast flow configuration. A slight modification to the RNAV departure routes in this area permitted the RNAV and VOR traffic to operate on a compatible basis.

6.1.5.2 The 1977 Task Force Concept at San Francisco

Strict application of the Task Force terminal area model at San Francisco was not possible due to the problem of conflicting routes from the three major airports considered in the terminal area design. An octant pattern was established at the perimeter of the 45 nm terminal area, but traffic flows inside of the perimeter were modified to permit compatible traffic flows to the three airports.

The technique of creating the 1982 terminal design before applying the 1977 terminal design concept worked quite well in San Francisco just as it did in Miami. The transition from a 1977 design concept to a 1982 design concept is easily accomplished by removing the VOR routes and modifying any RNAV routes that were moved in the development of the 1977 design.

A route width of 2 nm would not cause any major modifications to the 1977 RNAV or VOR route structure. No closely spaced routes were used in the San Francisco area design. Consequently, the effect of going to a larger route width value should not create any problems in the terminal design.

6.1.6 Chicago

6.1.6.1 The 1977 Chicago Terminal Area Design

The octant pattern at the Chicago terminal area was centered at the ORD VORTAC which is located at

N41° 59' 15" W 087° 54' 17"

The octant was aligned with Runway 09-27 R/L at O'Hare.

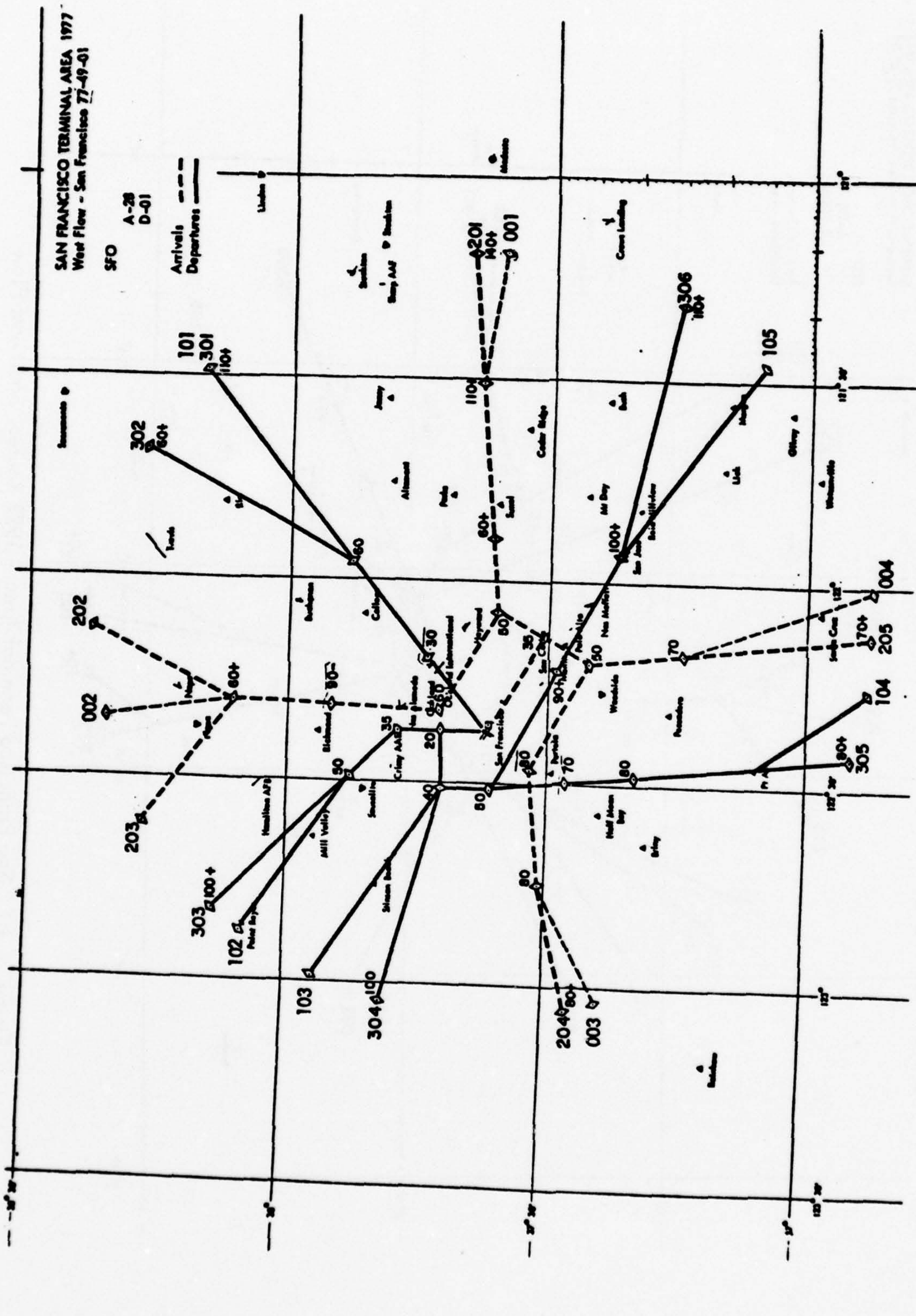


Figure 6.9 San Francisco Terminal Area - 1977 Routes, West Flow

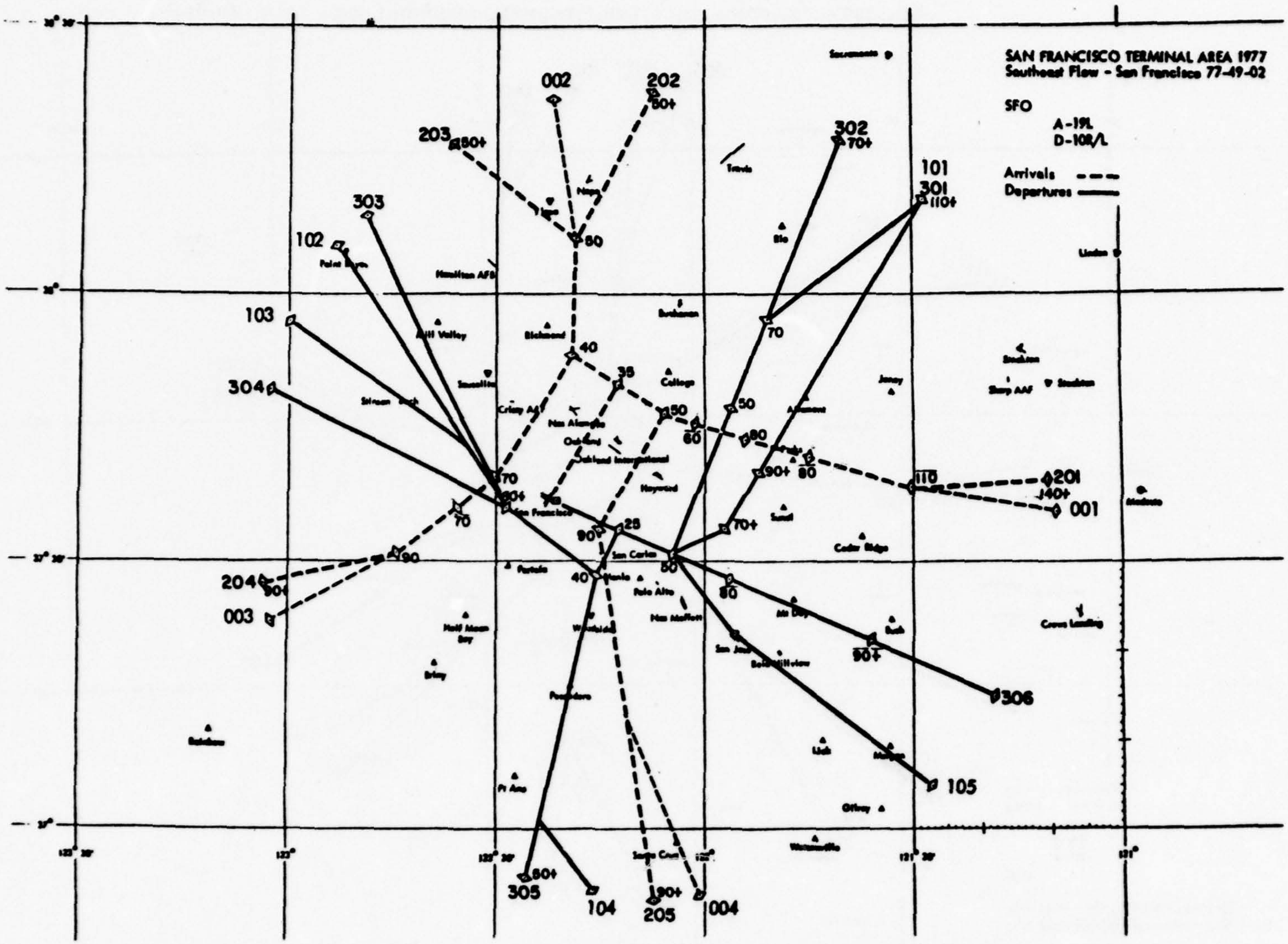


Figure 6.10 San Francisco Terminal Area - 1977 Routes, Southeast Flow

The 1977 Chicago O'Hare terminal designs are shown in Figures 6.11 and 6.12 for the southeast flow and west flow respectively. It can be seen that the 1977 conventional routes differ very little from their 1972 counterparts. The same flow patterns and similar altitude assignments have been made in arrival and departure octants. A few conventional routes have been deleted in order to provide for some independent RNAV arrival and departure routes outside of the feeder fixes.

Several independent RNAV routes have been added to the O'Hare traffic patterns. Where there was insufficient room to provide independent RNAV routes, the RNAV and conventional VOR or radar vector routes were combined. In order to provide for the high density O'Hare traffic and to provide the minimum path length, three arrival and departure routes were developed for each octant. In the case of arrivals, these three routes were combined into a single flow at or before the low altitude arrival waypoints. The location of these waypoints was based upon attaining compatible conventional and RNAV tracks. Departing traffic on the RNAV routes is demerged as soon as airspace is available in order to avoid excessive in-trail restrictions.

Midway RNAV arrival and departure routes overlie the conventional tracks in the terminal maneuvering area (inside of the feeder fixes of Joliet and Chicago Heights VORTACs). Outside of the feeder fixes independent routes were developed where there was sufficient airspace. The 1977 Midway terminal area designs are shown in Figures 6.13 and 6.14 for the southeast flow and west flow respectively. The RNAV and conventional routes for 1977 at Midway have essentially the same flow patterns and altitude assignments as the 1972 Midway patterns.

6.1.6.2 The 1977 Task Force Concept at Chicago

The present 1972 Chicago terminal area route structure is so well aligned to an octant flow configuration that very few design changes were necessary in order to develop a 1977 terminal route structure which was entirely compatible with the 1977 Task Force design concept. The basic VOR route structure from the 1972 design was the first route structure developed in the 1977 Chicago design. Then RNAV routes were developed according to the octant concept and in locations both in the terminal maneuvering area and the terminal transition area that were compatible with the VOR traffic flow. This design technique differed considerably from the technique employed at Miami and San Francisco.

The 1977 Chicago traffic flow is compatible with the 1977 Task Force concept in both the terminal maneuvering area and in the terminal transition areas. Slight modifications from the Task Force concept in the flow in the terminal maneuvering areas for O'Hare are necessary to account for the complex runway structure. No difficulty was encountered in applying the design concept at either O'Hare or Midway.

In general very few severe altitude restrictions are necessary in the Chicago area. There are surprisingly few restrictions, in fact, considering the complexity involved with the heavy traffic flows and the two airport operations at Chicago.

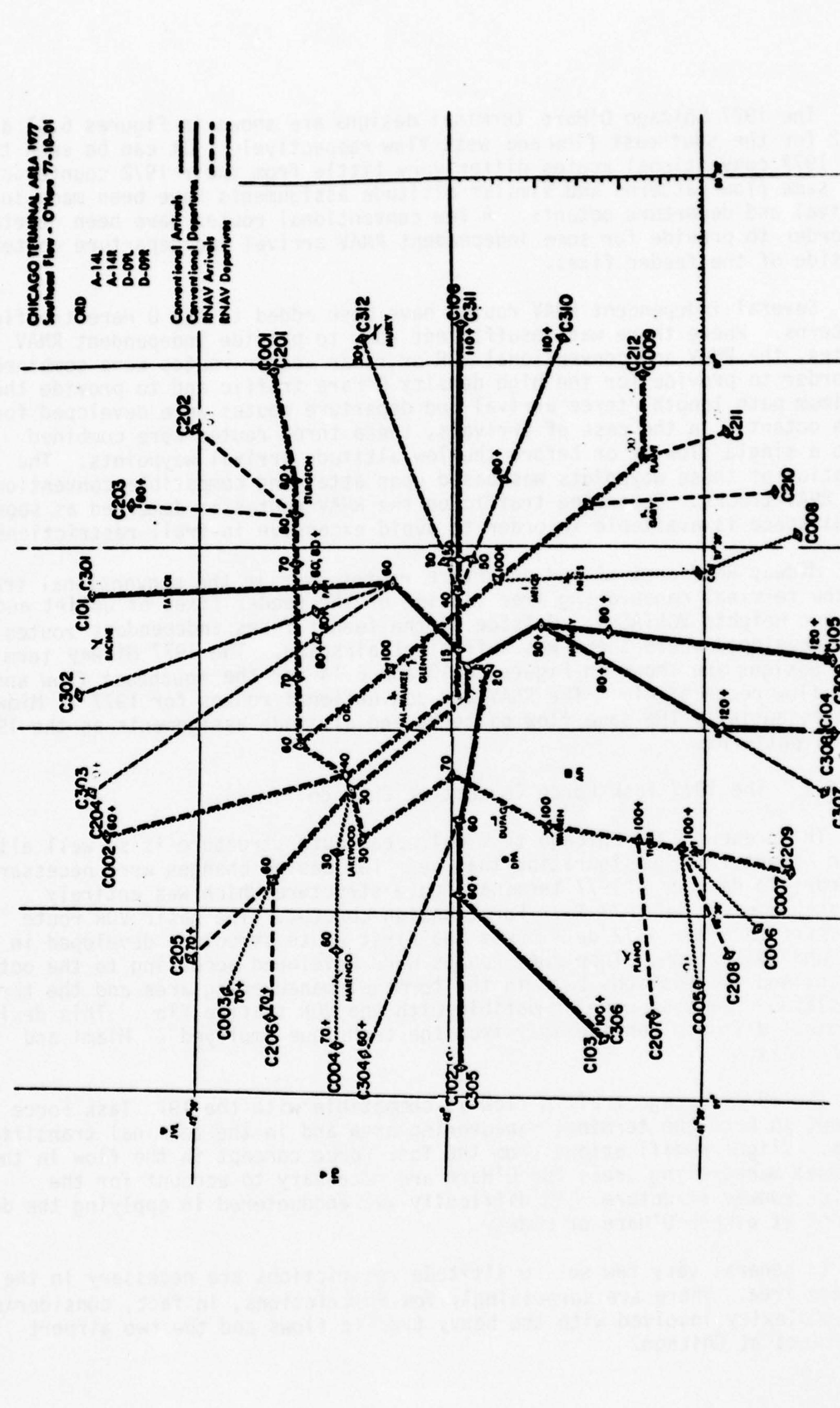


Figure 6.11 Chicago Terminal Area – 1977 Routes, O'Hare, Southeast Flow

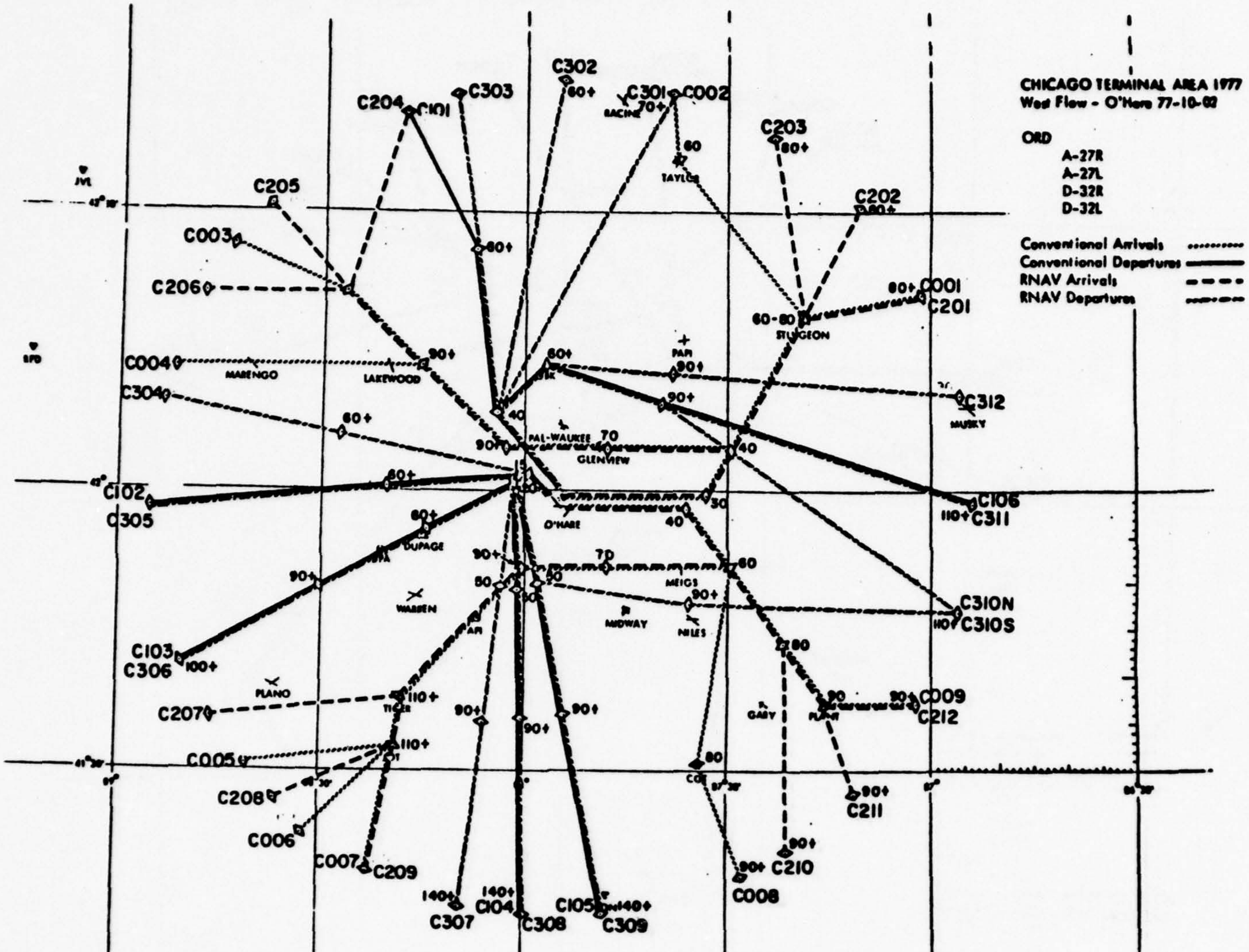


Figure 6.12 Chicago Terminal Area - 1977 Routes, O'Hare, West Flow

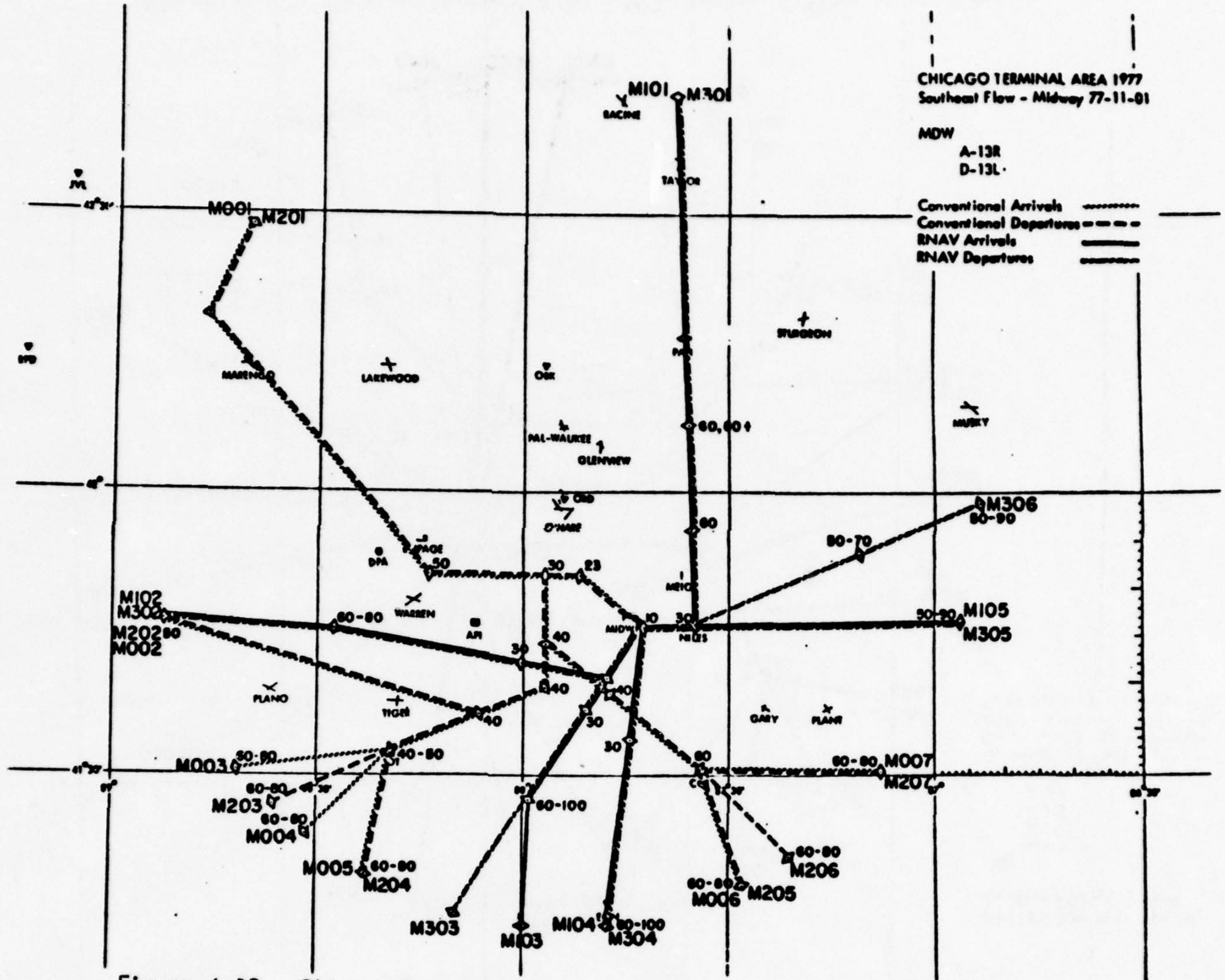


Figure 6.13 Chicago Terminal Area - 1977 Routes, Midway, Southeast Flow

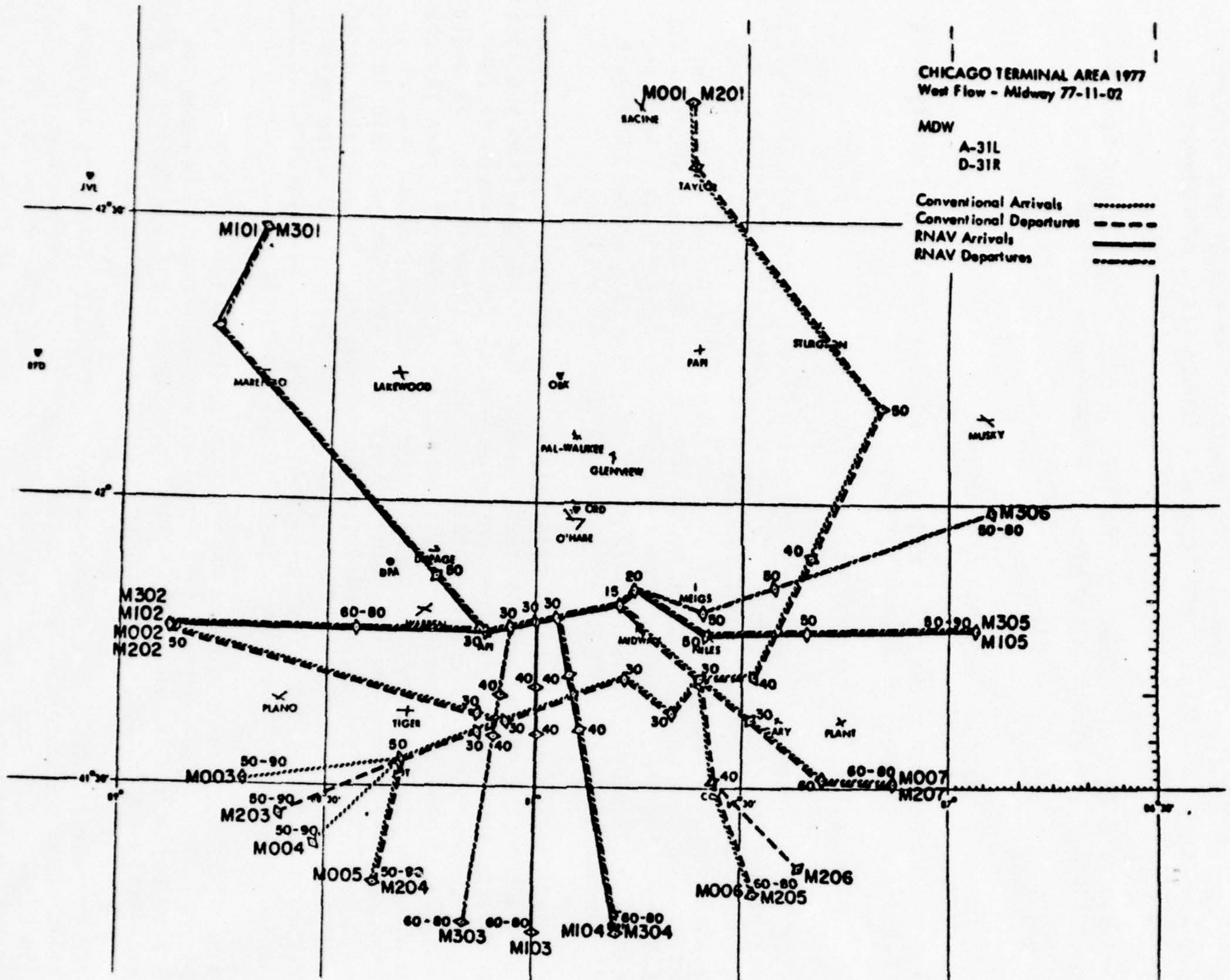


Figure 6.14 Chicago Terminal Area - 1977 Routes, Midway, West Flow

Holding pattern areas were located at the feeder fix locations at Plant, Sturgeon, Joliet and the unnamed location northwest of the O'Hare airport. Sufficient airspace exists at these locations should these procedures be necessary.

The use of 2 nm route widths in the 1977 Chicago area did not have a detrimental effect on either the O'Hare or Midway route structures.

6.1.7 New York

6.1.7.1 The 1977 New York Terminal Area Design

The octant pattern at New York was centered at a location slightly west of La Guardia at the following location:

N 40° 47' 16"   W 073° 54' 39"

With this location and a 47 nm radius the major feeder fix locations in present use fell within the octant pattern. The octant pattern was oriented according to the Runway 04-22 configurations that are the primary IFR runways at each of the three major airports. In addition to the routes to the three major airports a STOL port was assumed to be located on the New Jersey shore of the Hudson River. The 1977 terminal area design for New York for southwest and northeast flow is shown in Figure 6.15 and 6.16. The 1977 design considers traffic flow into the three major airports and the STOL port.

The 1977 design contains a considerable mixture of RNAV routes, conventional VOR and radar vector routes and combined routes. Major changes from the 1972 design include the rerouting of west arriving Kennedy traffic south of the Newark and La Guardia traffic rather than over Empire Intersection. In addition, the arrival and departure routes for all three airports begin to take the shape of the parallel routes which characterize the 1982 design. Route separation for these parallel routes has been kept at six miles wherever possible in order to permit parallel offset paths and delay fan techniques. Considerable airspace has been reserved in the region of the base leg for each of the three major airports to provide the controller with a final approach maneuver area so that spacing techniques can be applied prior to final approach.

Some difficulty in developing smooth flow patterns for the STOL port were encountered. The design which finally evolved was a compromise between the smooth flow patterns described by the Task Force Report and the desire to provide non-interfering routes for the STOL facility.

The problem of compatible flow between the adjacent TRACONS of New York and Philadelphia was investigated. Routes handling this traffic are shown in Figures 6.17 and 6.18. The low altitude departure waypoints at Philadelphia were connected by a direct route to the low altitude arrival waypoint for each of the three New York area airports plus the assigned STOL port and vice-versa. The constraints imposed by the terminal waypoint locations do introduce several "doglegs" into these low altitude routes. In addition several crossing route situations occur which would have to be handled by the

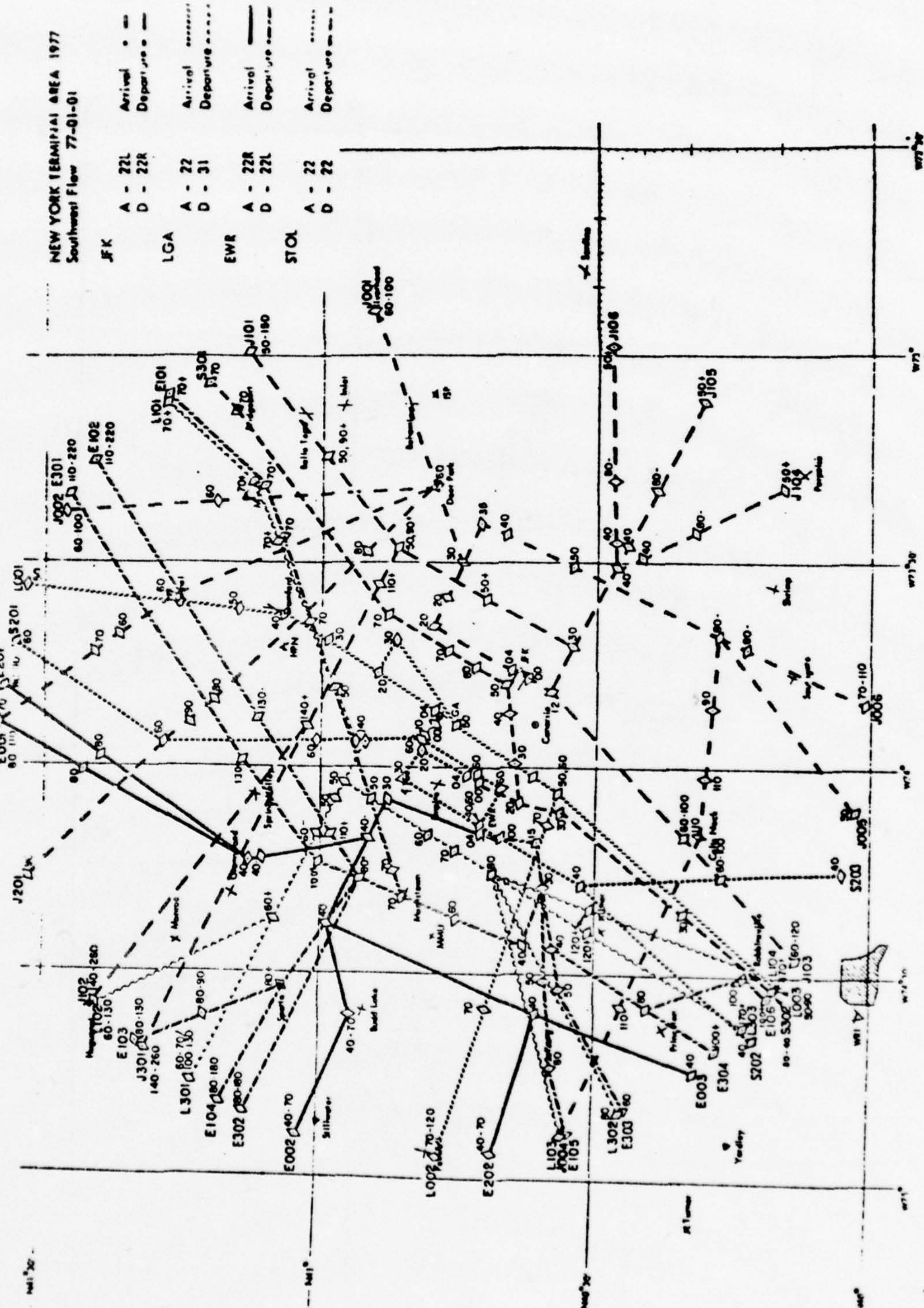


Figure 6.15 New York Terminal Area - 1977 Routes, Southwest Flow

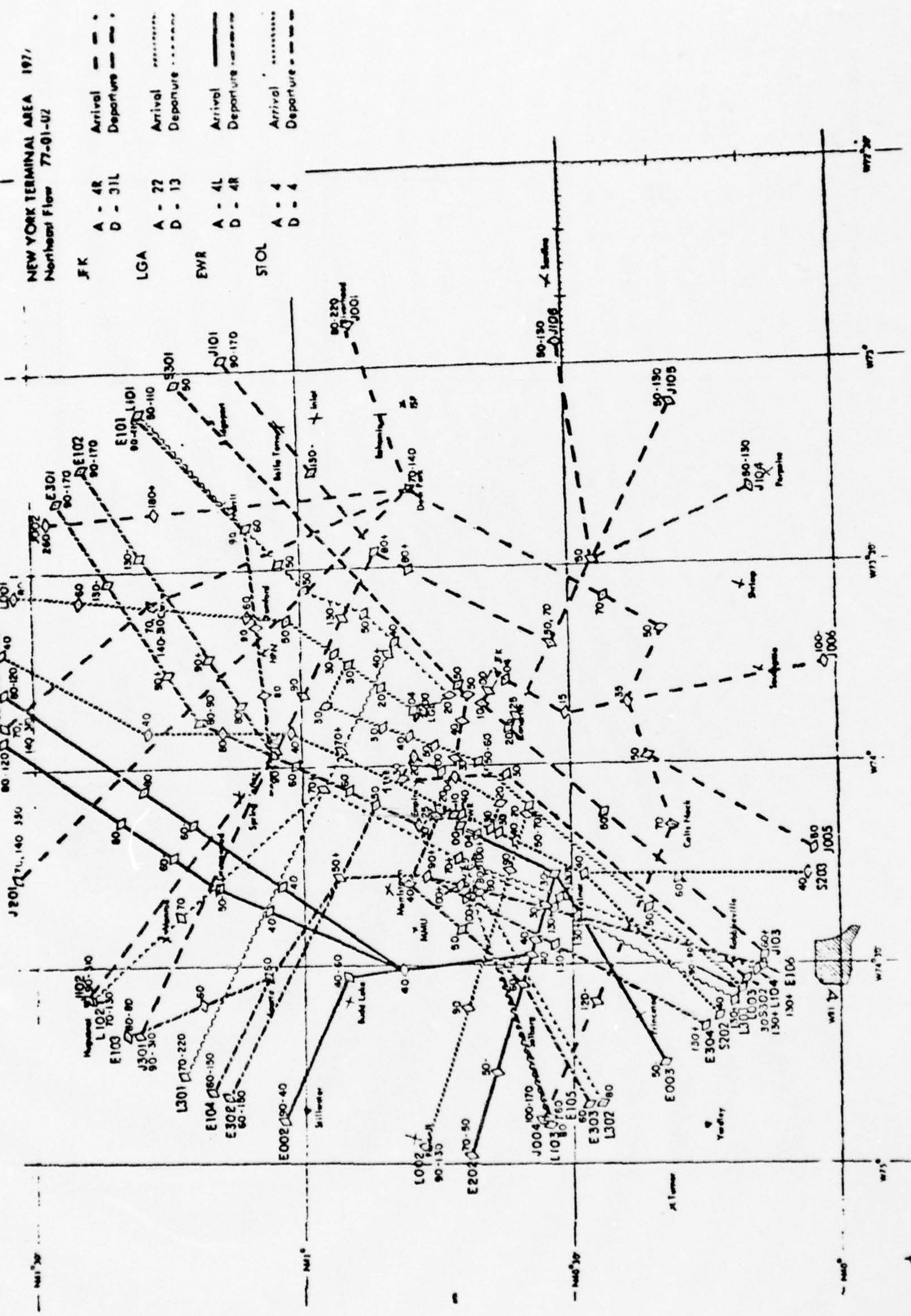


Figure 6.16 New York Terminal Area - 1977 Routes, Northeast Flow

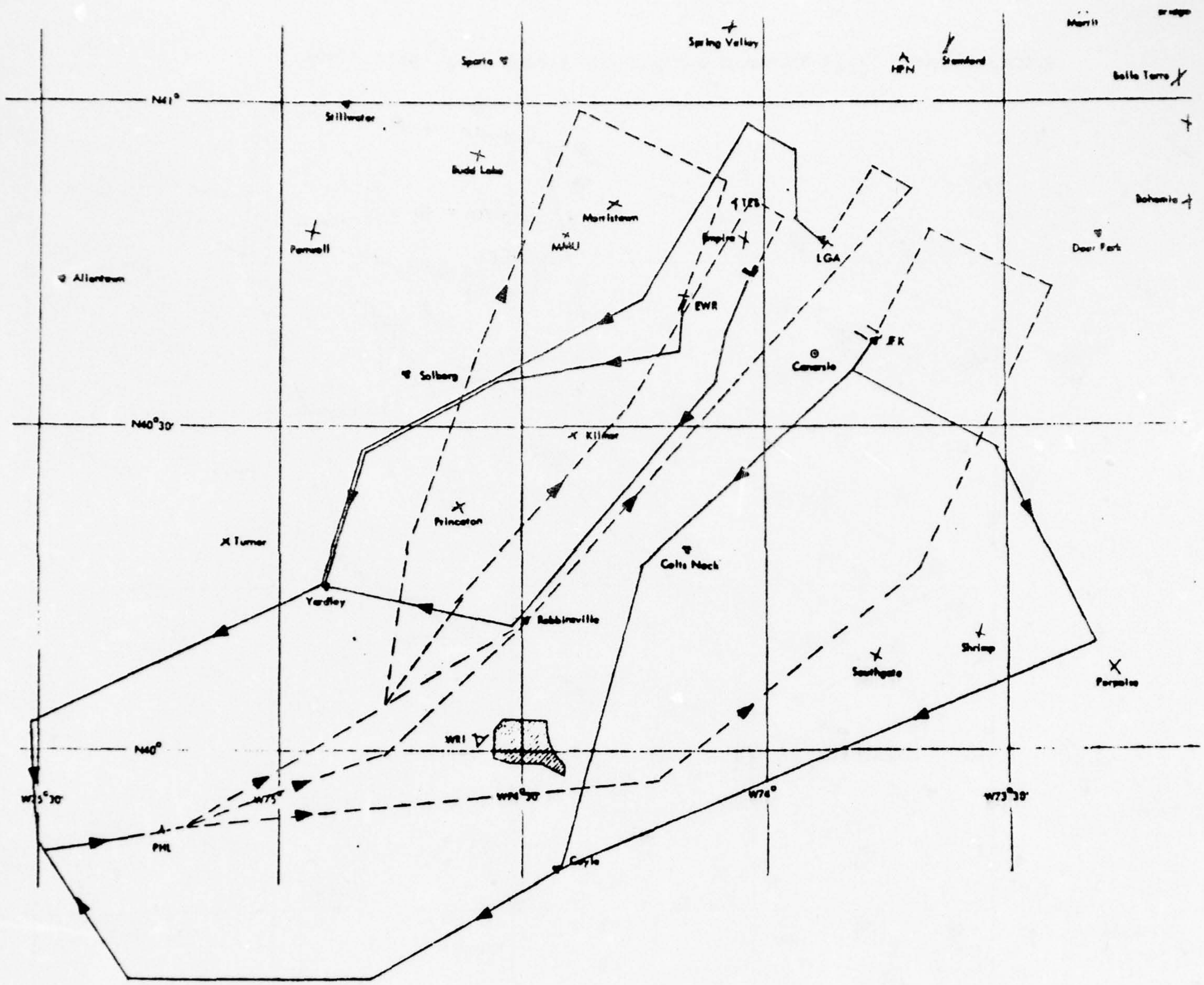


Figure 6.17 New York - Philadelphia Interface 1977, Configuration 1

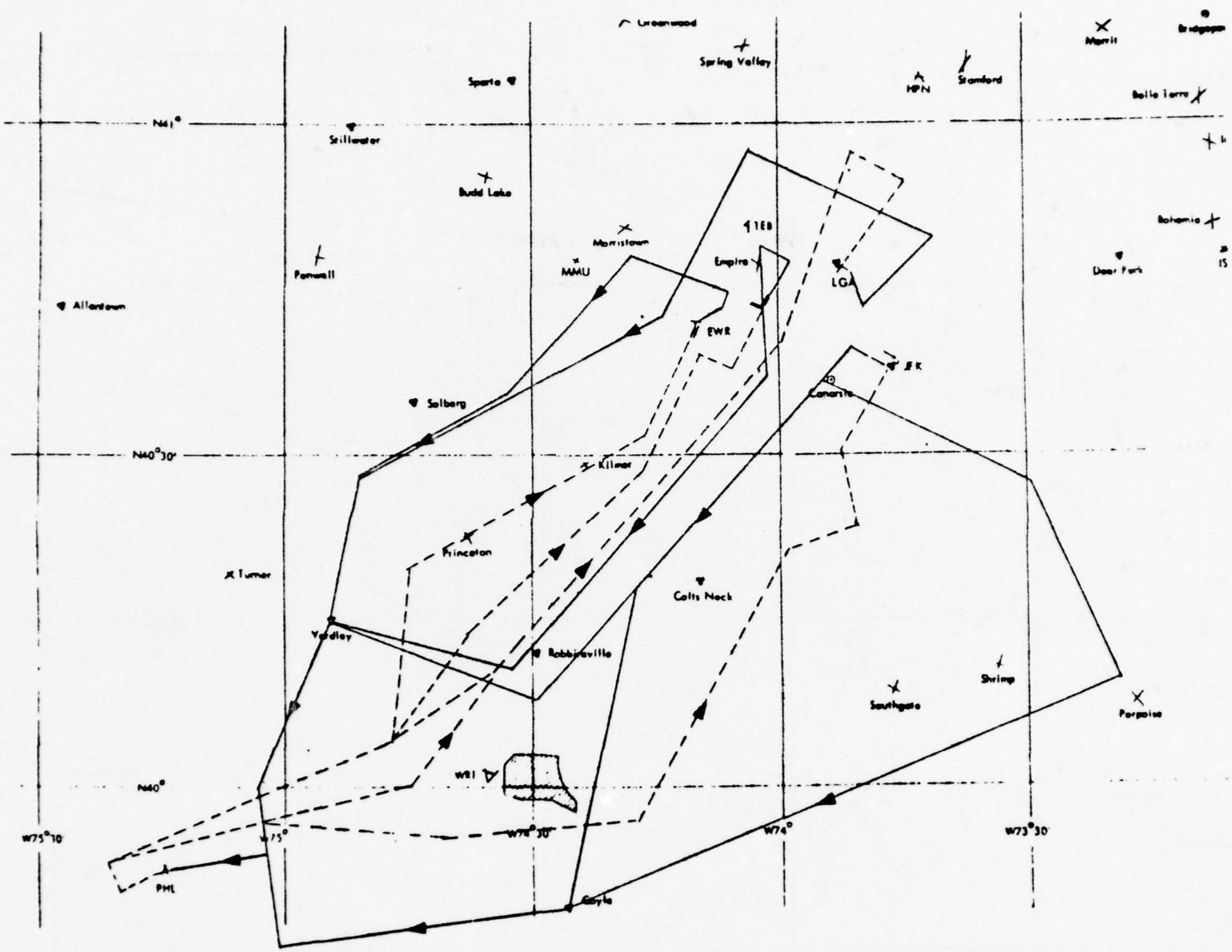


Figure 6.18 New York - Philadelphia Interface 1977, Configuration 2

controller or by altitude assignments in order to provide positive separation assurance. However, as depicted by Figures 6.17 and 6.18 a reasonably compatible traffic flow between the New York and Philadelphia area can be established by applying the Task Force Terminal area design guidelines for this transition time period. A reasonable, compatible flow can be established as depicted by these diagrams.

With the number of crossing routes that are necessary in New York, it is virtually impossible to develop many routes which have no altitude restrictions. However, every attempt was made to minimize the number of restrictions for both arrivals and departures.

6.1.7.2 The 1977 Task Force Concept at New York

The application of the octant concept at New York produced a terminal design with numerous altitude restriction and crossing route situations. The major difficulties involved in creating this complex design was concerned with getting Kennedy arrivals and departures to the west through the route structures of the other major airports and in getting Newark departure traffic out to the northeast.

Traffic patterns in the terminal maneuvering areas follow generally along the 1972 route patterns rather than that of the Task Force model. This situation is necessary due to the conflicting nature of the terminal transition areas in this complex terminal area.

A specific analysis of route width and holding pattern airspace problems at New York was not performed. However, a problem does appear to exist in providing holding airspace on those arrival routes which have very little vertical airspace available. Route J004 in Figure 6.15 is an example of such a route.

6.2 1977-1982 2D RNAV DESIGN ANALYSIS

The analysis of the 1977-1982 terminal area designs consisted of essentially the same type of analysis that was given to the 1972-1977 designs. First, a comparison of the seven designs with the Task Force terminal area model was undertaken and second, a real time simulation of the New York 1977 terminal area route structure was performed at NAFEC in a mixed VOR/RNAV environment during the transition period.

6.2.1 Application of the 1977-1982 Task Force Concepts

In the 1977-1982 time period the Task Force Report [1] calls for the implementation of the terminal design concept at all radar terminals and the establishment of 2D RNAV routes at all of these terminals.

In all seven terminals the Task Force terminal model was applied to the terminal area design. In all cases an octant flow pattern was developed at the perimeter of the terminal area. Inside the terminal area the Task Force model was applied successfully to all of the terminals except two. Those two were San Francisco and New York.

In these two terminals the traffic patterns in the terminal maneuvering area are such that the flows to and from the multiple airports in both of these areas produce excessive demands upon the available airspace. As a result crossing routes and altitude restrictions are necessary to produce orderly traffic patterns without excessive distance penalties to the user. However, in order to resolve this problem modifications of the standard Task Force concept were developed and applied to New York and are described in Section 7.

The design techniques that were used to develop the seven 1977 terminal areas ranged from use of the 1972 route structure in the case of Philadelphia, Denver and Chicago to using the 1982 RNAV route structure in the case of New Orleans, Miami and San Francisco. The New York design fell somewhere in between these two extremes. Of the two techniques, the one in which the 1982 RNAV route structure is developed prior to any consideration of the 1977 design appeared to produce more satisfactory designs from the standpoint of organized route structures. The one problem which can occur, however, is that the existing VORTAC locations may not produce a satisfactory VOR route structure which overlies the 1982 RNAV route structure. This situation did not occur in the New Orleans, Miami and San Francisco areas but it is a distinct possiblility in areas where few VORTACs are available. Such terminals would require alternative VOR route design procedures. This would no doubt impact upon the 1977-1982 RNAV route structure as well.

6.2.2 Validation of the 1977-1982 Design Concept

The validation of the 1977-82 RNAV terminal design concept consisted of the development of the seven terminal designs and the real time simulation of the New York 1977 terminal design.

6.2.2.1 1977-1982 RNAV Route Design

The development of RNAV route designs for the second stage of RNAV implementation produced designs for two traffic flows at ten airports in the seven terminal areas for a total of twenty terminal route designs. The Task Force design concept was applied to five of these terminal areas while an alternate procedure was necessary at the metroplex terminals in New York and San Francisco. The alternate design procedure made use of the octant concept but considerable changes to the Task Force model were made in the terminal maneuvering area traffic patterns in order to accommodate the traffic flows demanded by these multiple airport terminals. It is important to note, however, that in all twenty 1977 designs, compatible RNAV and VOR route structures were developed whether the design technique made use of the Task Force model or some alternate terminal model.

6.2.2.2 1977 Real Time Simulation

The 1977 New York real time simulation experiment [13] was essentially similar to the 1972 time period simulation except for two factors.

First, the route structure used in this simulation was patterned after the 1977 New York terminal design, and second, the percentage of RNAV traffic

was varied in four steps from 25% RNAV to 100% RNAV.

As in the case of the 1972 simulation the results can be categorized into the controller workload category and the controller handling techniques category. The results of the workload analysis are presented in Figure 6.19, 6.20 and 6.21. These statistical summaries of radio contacts, communications time and RNAV clearances as a function of the percentage of RNAV traffic show essentially the same results as the 1972 terminal simulation.

The number of radio contacts and the total controller talk time decreases significantly as the percentage of RNAV aircraft increases. The radio contacts are virtually identical in the 1972 and 1977 results while the total communications time decreased slightly more in 1977 than in 1972. The percentage of RNAV arrival clearances broken decreased considerably as the percentage of RNAV traffic increased. However, the percentage of broken clearance levels were greater in 1977 than in 1972. For departures the broken clearance level remained a constant 6% which is virtually identical to the 1972 results.

The controller instruction data summaries are shown in Figure 6.22, 6.23, 6.24 and 6.25. These data show exactly the same trends as do the 1972 data. A large decrease in the number of flight path control instructions with increasing use of RNAV is indicated in Figure 6.22. In Figures 6.23 to 6.25, the composition of these control instructions is depicted. A significant decrease in radar vector instructions is noted as the RNAV participation level increases while the use of RNAV instructions such as "parallel offset" and "direct-to-waypoint" increase in frequency by a considerable amount.

In general the overall simulation results for the controller are consistent and tend to favor the RNAV operations.

6.3 FINAL 1977-1982 TERMINAL AREA DESIGNS

No specific "final" 1977-82 terminal area designs were developed. This is due to a change in the recommended RNAV terminal area design guidelines from those which were suggested by the RNAV Task Force. The Task Force recommended the time phased design approach covering the time period from 1972-1982. The recommended terminal area design guidelines which resulted from this study make use of an initial RNAV design which is based on the existing VOR/radar vector route structure and a "final" RNAV terminal area route structure which is based upon enroute traffic flow. The selection of arrival and departure areas in this final design is purposely made to correspond as close as possible to the traffic flows that are currently used in the VOR/radar vector environment. This correspondence provides for ease of implementation by ATC and early implementation so that RNAV users can derive early benefits from the use of RNAV in the terminal area. In many cases RNAV routes in the terminal area can be implemented as soon as there is a user demand for these routes. As a result, the interim time period in which there will be a mixture of VOR/radar vector and RNAV traffic will be based more upon the user demand for RNAV routes rather than a specific alignment of arrival and departure areas according to some standard pattern such as the Task Force model. In this manner the terminal area route structure may evolve from that of being basically VOR/radar vector routes to that of being primarily RNAV routes in an orderly progression and also provide benefits to the users at an early date.

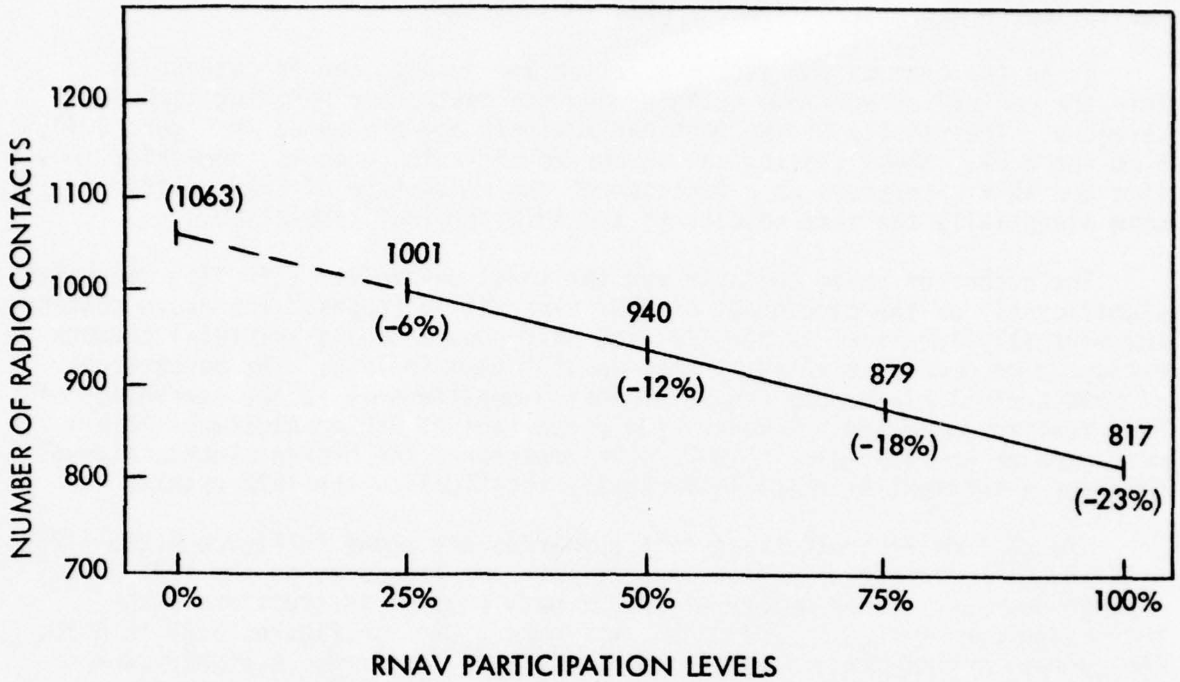


Figure 6.19 Number of Radio Contacts

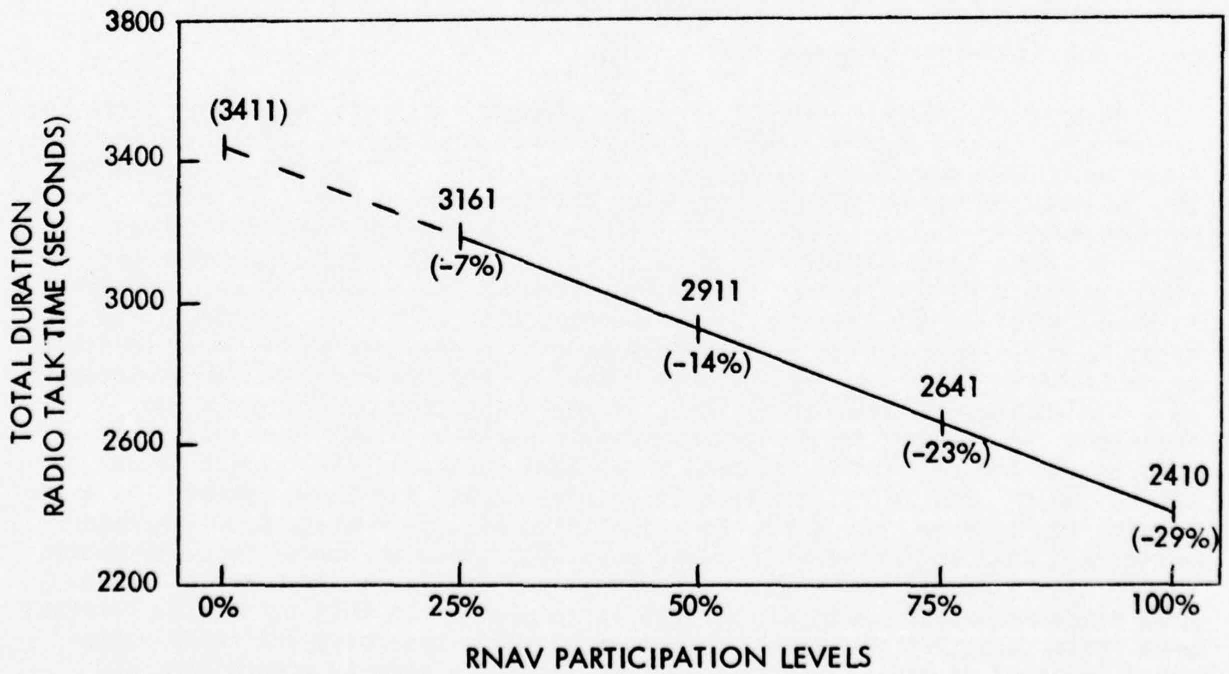


Figure 6.20 Radio Communications Time

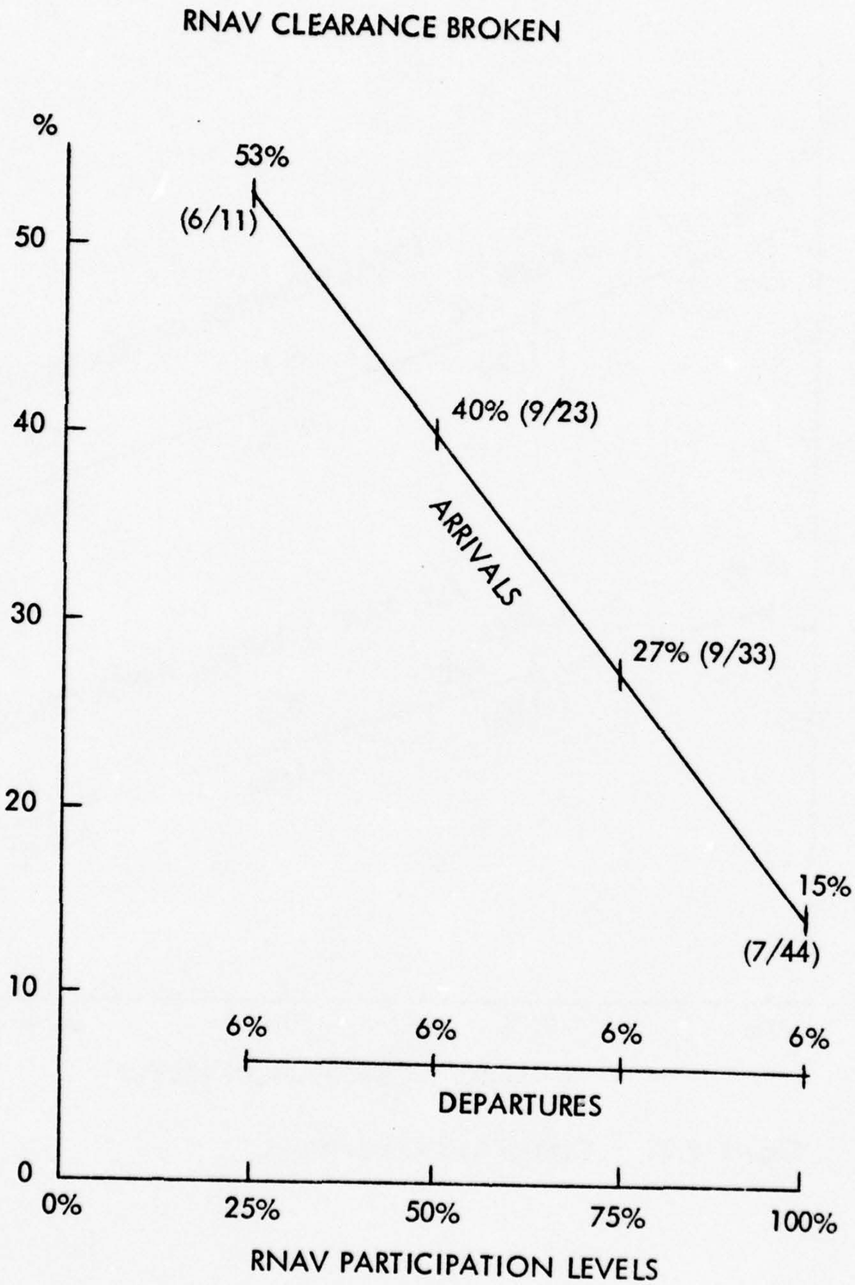


Figure 6.21 RNAV Clearances Broken

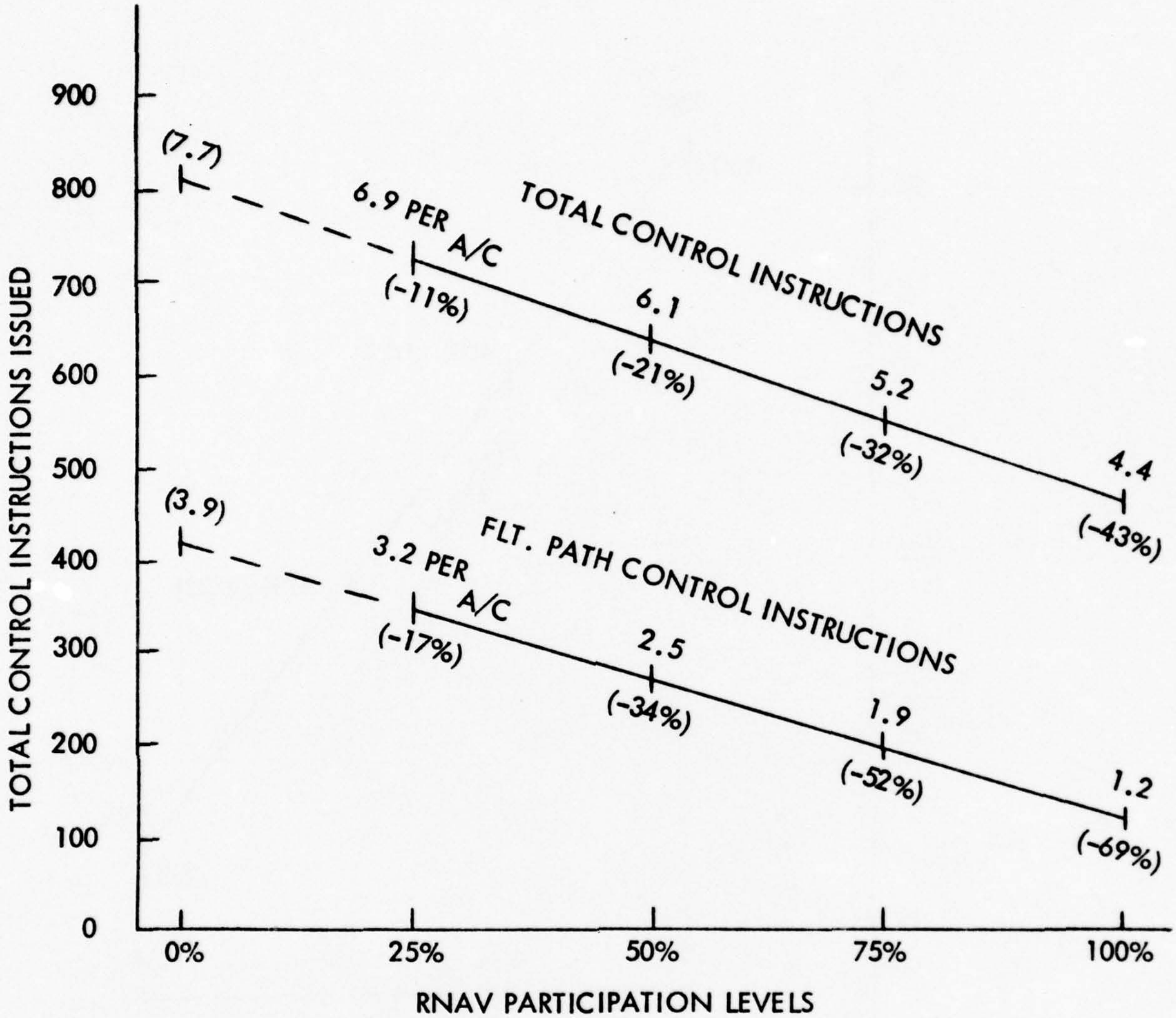


Figure 6.22 Control Instructions Issued

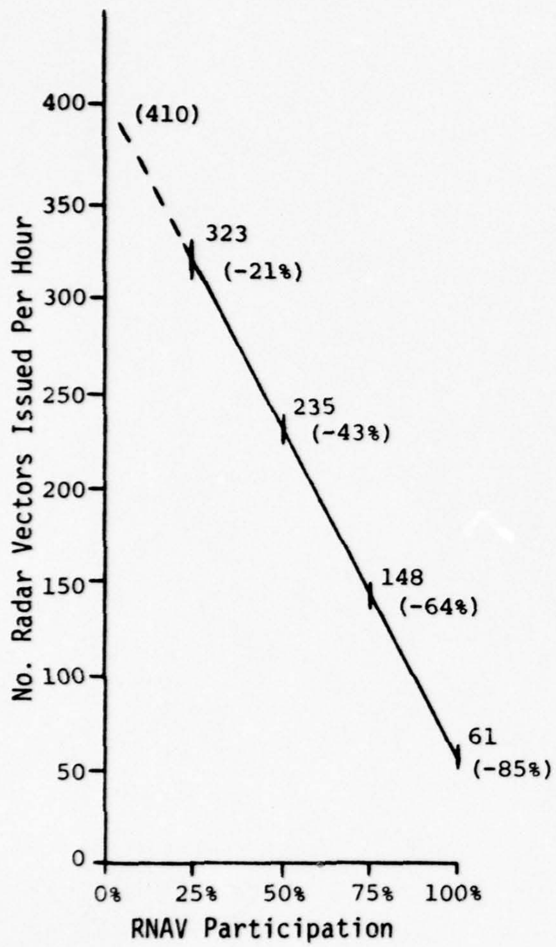


Figure 6.23 Radar Vectors Issued

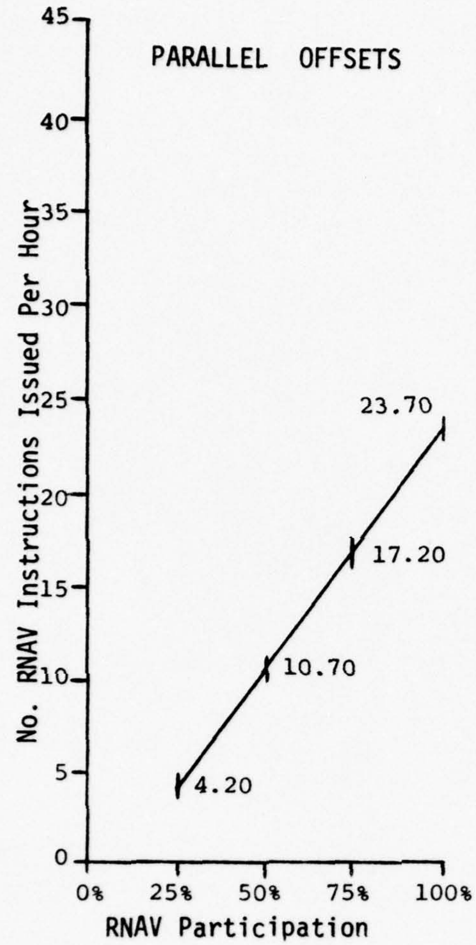


Figure 6.24 Parallel Offsets

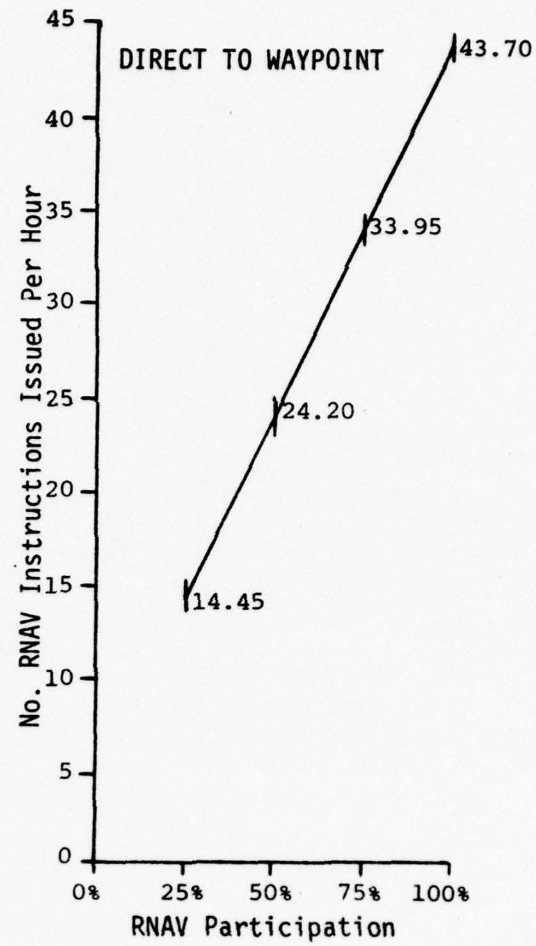


Figure 6.25 Direct To Instructions

7.0 POST-1982 DESIGNS AND ANALYSIS

The Task Force terminal area model of Section 3 was applied to the seven terminal areas in order to develop initial RNAV terminal area route structures which were in accord with the Task Force recommended terminal design concept. Two runway configurations were selected for each terminal area. Descriptions of the Task Force model designs are contained in Section 7.1.

The initial designs were then analyzed for correspondence to the Task Force model and for impact on both the ATC system and the user, as described in Section 7.2. Additionally, fixed gradient VNAV designs were developed for the New York and New Orleans terminal areas. These designs were analyzed to determine the ATC system impact and to ascertain if user benefits would be produced through the use of these designs. The fixed gradient VNAV designs and analyses are discussed in Section 7.3.

The analyses of the initial post-1982 2D RNAV and VNAV designs indicated that some modifications were necessary in the Task Force design guidelines. A modified set of guidelines was developed. In order to validate these modified guidelines, they were applied to the New York terminal area and the resulting modified design was analyzed for user impact. These modified guidelines and the corresponding New York designs are discussed in Section 7.4.

The southwest flow of the modified New York terminal design for the post-1982 time period was used as the basic route structure for a real time simulation program at NAFEC [18]. This simulation effort included several features that were not considered in the two transition period simulations that were discussed in Sections 5 and 6. These differences are as follows:

1) A route structure based on modified RNAV terminal design concepts rather than strict Task Force design guidelines.

2) The inclusion of additional airport capability such that airspace rather than airport capacity would limit arrival traffic.

3) The addition of VNAV equipped aircraft and VNAV ATC procedures.

4) The use of general aviation aircraft simulators to generate GA radar targets.

5) The consideration of VNAV "stacked route" arrival procedures.

6) The generation of radar targets with avionics error characteristics.

The results of the simulation relative to the terminal route structure are discussed in Section 7.4.3.4.

The modified guidelines were reviewed with user groups and controllers from the appropriate regions, as discussed in Section 4.4 and recommended design procedures and guidelines were developed as described in Sections

7.5 and 8.0 respectively. Modifications to the 1972-1977 designs resulting from the application of comments received from the controllers were described in Section 5. The application of the recommended terminal area design guidelines to the post-1982 terminal areas is described in Section 7.5. The reader is referred to Figure 2.1 for a summary of the progression from the initial seven designs (based on Task Force Model) to the modified New York post-1982 design (based on the modified guidelines to the final 1972-1977 and post-1982 designs for all seven terminal areas (based on the recommended guidelines).

7.1 Initial Post-1982 Terminal Area Designs

7.1.1 New Orleans

7.1.1.1 The Post-1982 New Orleans Terminal Area Design

The design of the post-1982 New Orleans terminal area proceeded generally along the same lines as the 1977 terminal design. The principal difference occurs when the flow patterns are established after the location of the octants and the arrival and departure fixes are determined. Since the 1982 design is based in part upon the assumption of 100 percent RNAV users, the routes are designed to make use of the RNAV flexibility in flying between any points within the coverage of the associated radio facilities. This permits the route designer to locate the arrival and departure fixes and their associated routes at the nominal Task Force model positions without regard as to whether the routes are on convenient VOR radials or not.

High Altitude Arrival Routes - Post-1982

Arrival and departure routes for high altitude New Orleans traffic is shown in Figures 7.1 and 7.2. The location of the high altitude arrival fixes on the 45 nm circle are based upon the high altitude traffic distribution diagram for New Orleans. Each high altitude arrival fix is located in an arrival octant at either the centerline of the octant or a point 15° on each side of the centerline whichever is closest to the direction indicated as described in Section 3. In cases where more than one arrival route per octant would be indicated by the traffic distribution diagram, any or all of the three 15° spaced points in the octant may be used. The use of multiple high altitude arrival waypoints can be seen in three of the four octants shown in Figure 7.1 and 7.2.

From the high altitude arrival waypoints the routes proceed inbound in each of the four octants to the four low altitude arrival waypoints which are located on the octant centerline 28 nm from the center of MSY airport. This point corresponds to a feeder fix and hand-off point between Houston Center and New Orleans Approach Control.

From the low altitude arrival waypoint traffic on the two downwind sides of the airport proceeds directly toward the center of the airport until they intercept the downwind legs of the approach on each side of the airport. The downwind legs are parallel to the final approach course and are spaced

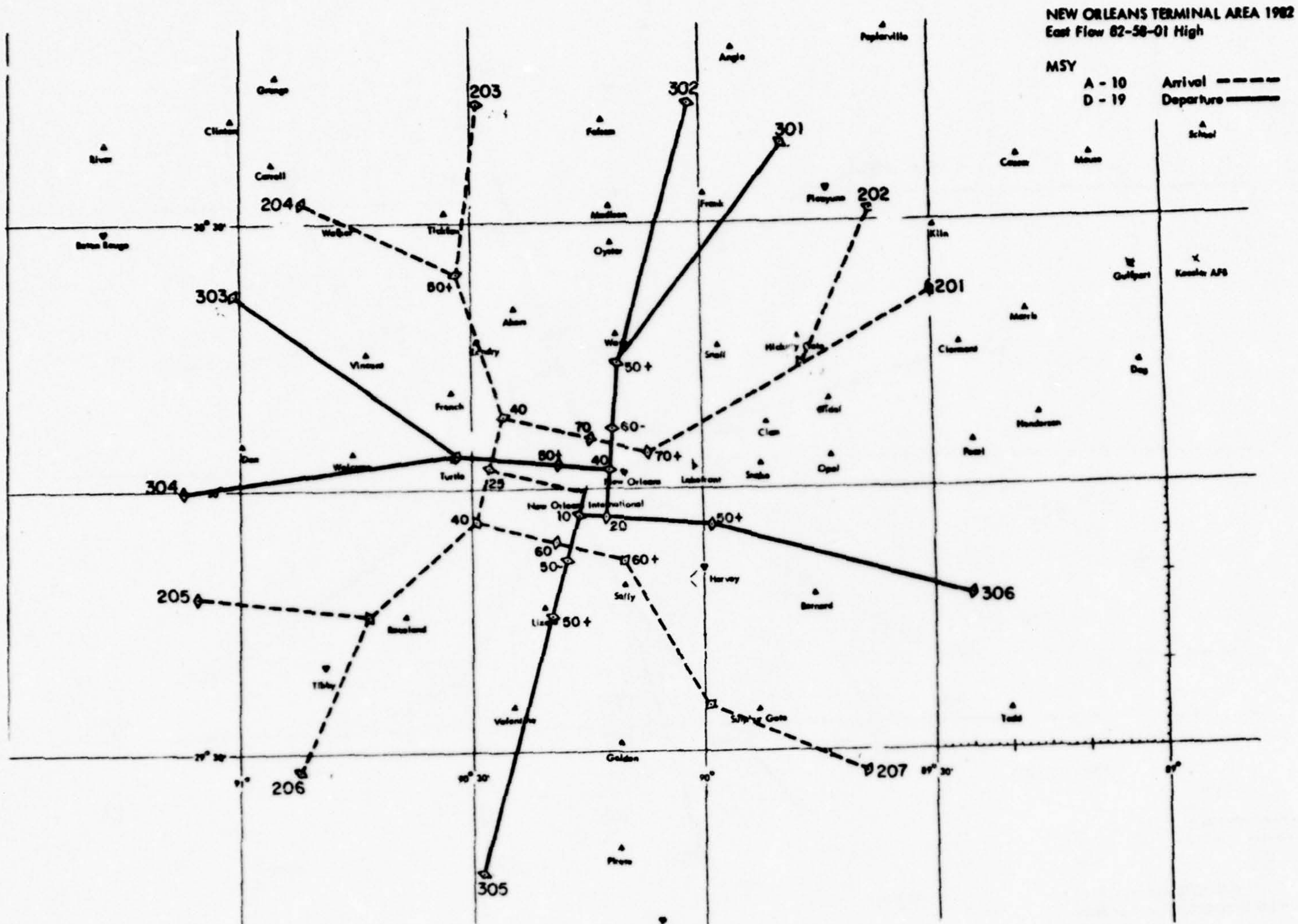


Figure 7.1 New Orleans Terminal Area - Post-1982 High Altitude RNAV Routes, East Flow

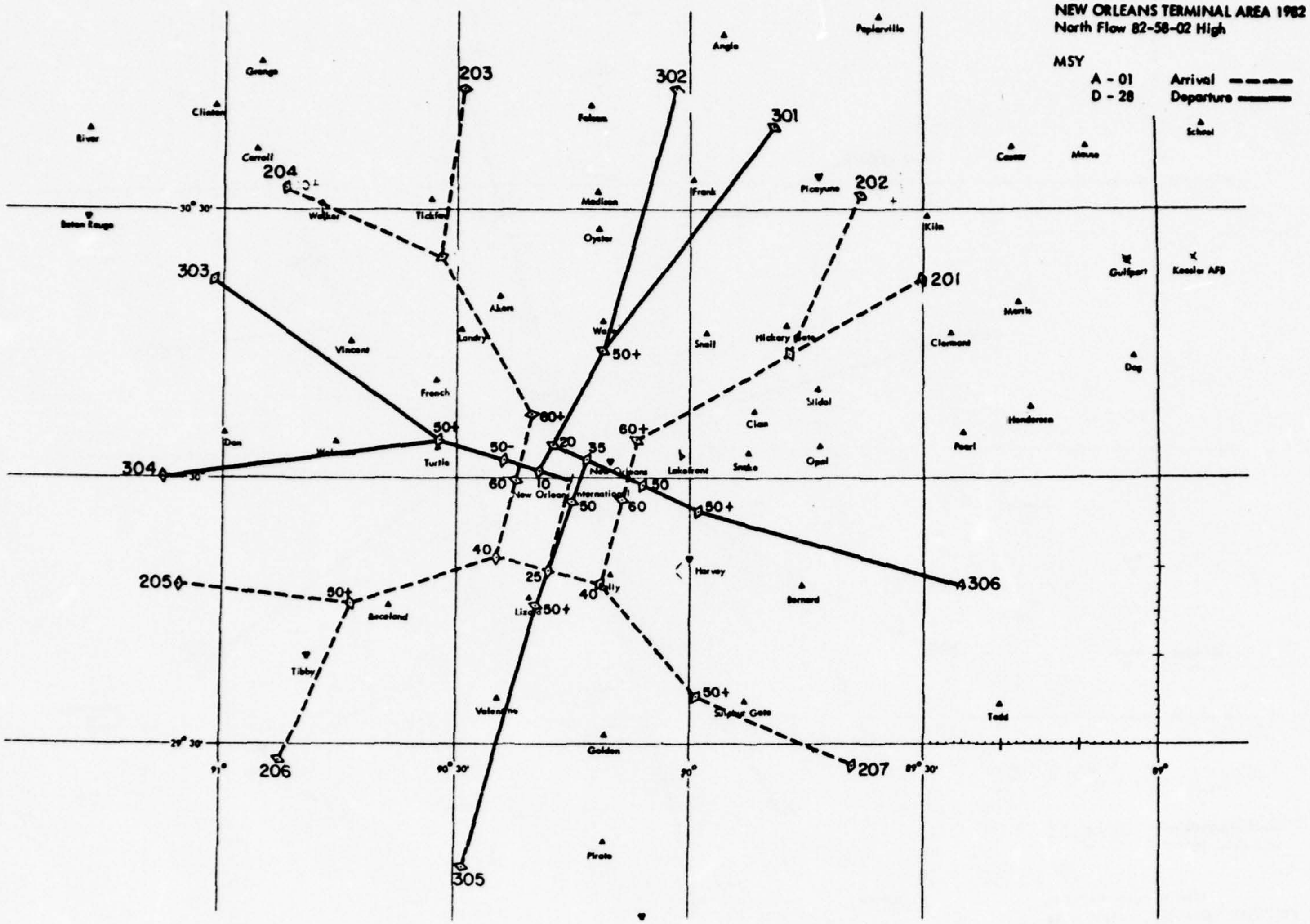


Figure 7.2 New Orleans Terminal Area - Post-1982 High Altitude RNAV Routes, North Flow

6 nm on either side. The arriving aircraft then proceed along the downwind leg until they reach the base leg which is located 10 nm from the arrival runway threshold. The intersections of the base leg and the downwind legs are the base leg turn waypoints. Traffic coming from the upwind side of the airport proceeds from the low altitude arrival waypoint to the closest base leg turn waypoint where they merge with traffic from the downwind side of the airport. From each of the base leg turn waypoints, the routes merge at the intermediate waypoint (IWP) which is on the final approach course 10 nm from the runway threshold at the intersection of the base leg and the final approach course. The final approach course has a final approach waypoint (FAWP) 5 nm from the threshold and a missed approach waypoint (MAWP) at the threshold.

High Altitude Departure Routes - Post-1982

The high altitude departure routes shown in Figures 7.1 and 7.2 were developed so that the departing aircraft climbs to a specified altitude while maintaining runway heading and then proceeds directly to one of four low altitude departure waypoints which are located on the centerline of each of the departure octants 15 nm from the center of the airport. The one octant where there is a slight variation in this procedure is in the octant in the direction of the final approach course. Departures using this octant make a climbing turn of 270° before proceeding to the low altitude departure fix. This allows these aircraft to gain sufficient altitude to remain clear of arrival traffic.

From the low altitude departure waypoint the aircraft proceed to a high altitude departure waypoint which is located in the departure octant 45 nm from the airport. The high altitude departure waypoint may be located on the centerline of the departure octant or 15° either side of the centerline. That selection is based upon the traffic distribution diagram for high altitude traffic. The point selected is the one which is most closely aligned with the direction of the destination city. As in the case of the high altitude arrival waypoints, up to three high altitude departure waypoints can be assigned per octant. In New Orleans one waypoint was used in two departure octants (south and east) and two waypoints were used in the remaining two octants (west and north).

Low Altitude Routes - Post-1982

Low altitude arrival and departure routes for the New Orleans 1982 design are shown in Figures 7.3 and 7.4. These routes are identical to the high altitude routes inside of the low altitude arrival and departure fixes. The section of these routes from the 45 nm circle into the low altitude fixes is considerably different than the high altitude routes. The low altitude arrival and departure routes merge at the 45 nm circle. It should be noted, however, that it is not a necessary constraint that the low altitude routes merge at this point. If an operational advantage can be obtained through the use of a one-way route, it is acceptable to have separate arrival and departure waypoints for the low altitude traffic on the 45 nm boundary of the terminal area. Thus low altitude traffic may violate the octant flow concept outside of the low altitude fixes in order that excessive distance penalties are not incurred on short routes.

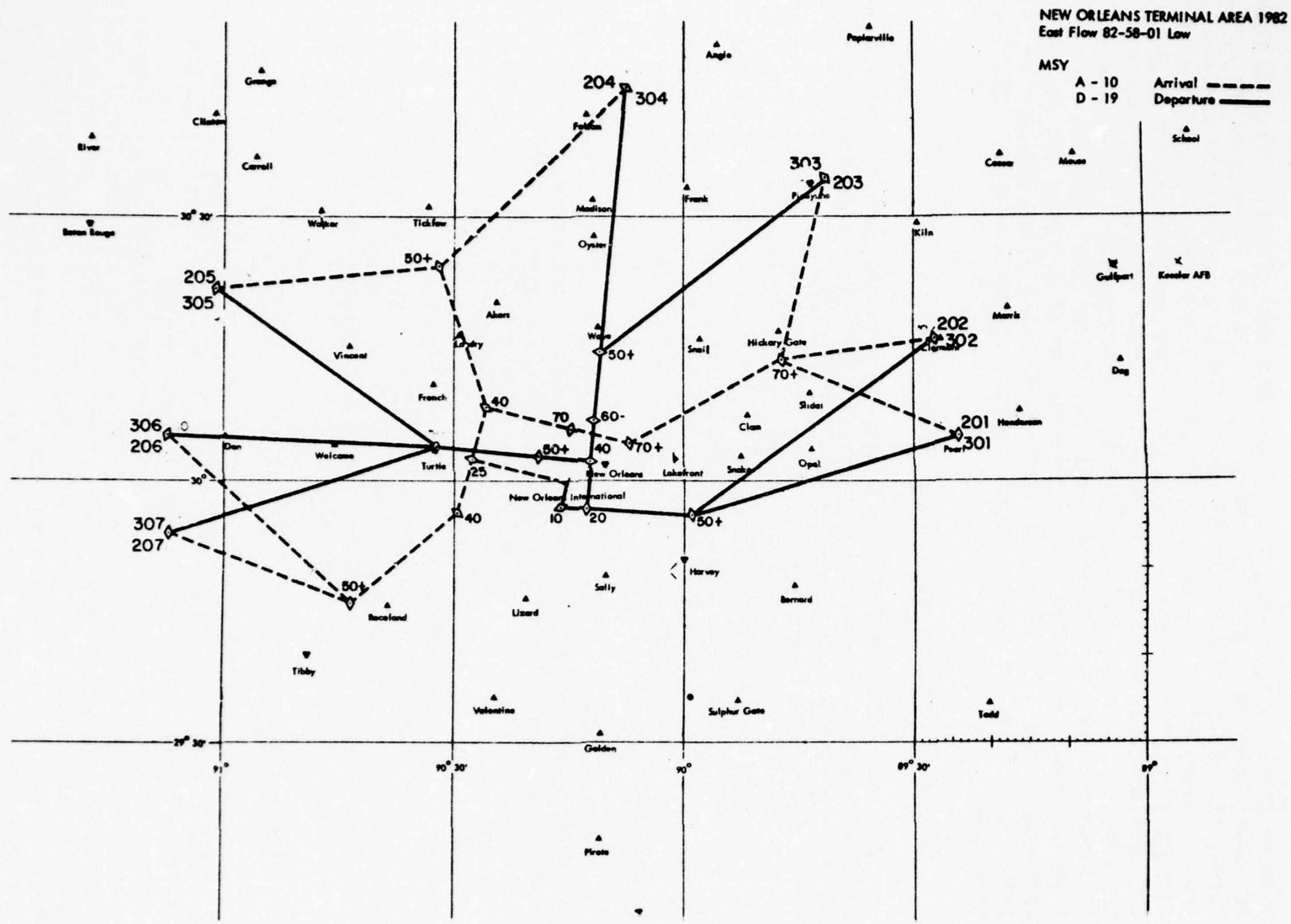


Figure 7.3 New Orleans Terminal Area - Post-1982 Low Altitude RNAV Routes, East Flow

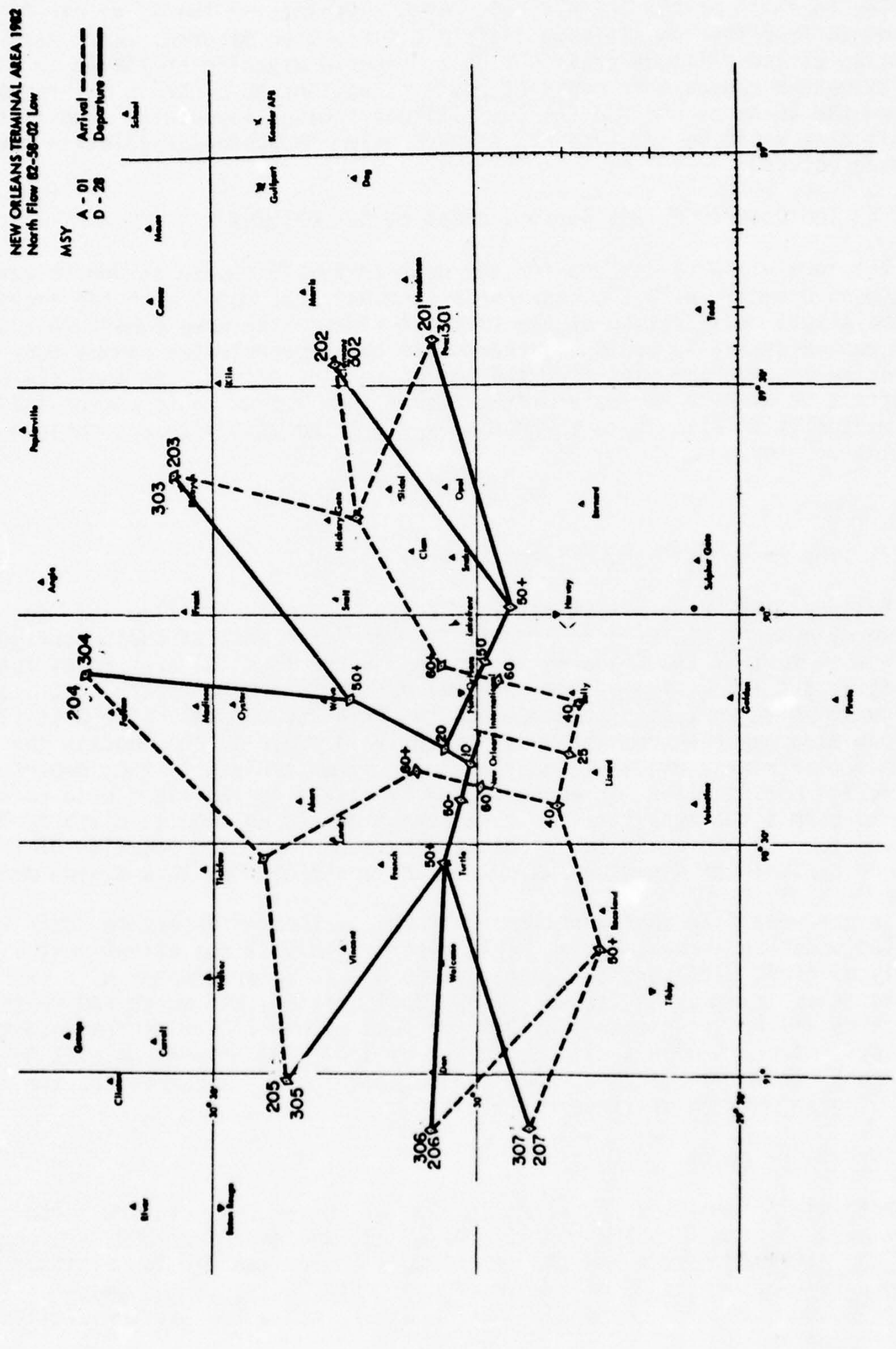


Figure 7.4 New Orleans Terminal Area - Post-1982 Low Altitude RNAV Routes, North Flow

The location of the low altitude merge waypoints on the 45 nm circle is determined from the low altitude traffic distribution diagram. Each major direction of low altitude traffic flow is given a waypoint at the 45 nm circle. This situation causes some crossing route situations to occur in the region between the 45 nm circle and the low altitude arrival waypoints. Conflicts in this area would be resolved by the controller in whose jurisdiction the crossing occurs.

7.1.1.2 The Post-1982 Task Force Concept at New Orleans

The terminal area designs for the post-1982 RNAV routes at New Orleans correspond directly with the Task Force terminal area model with the exception of some slight modification of the terminal maneuvering area departure routes which was necessary in order to accommodate the perpendicular runway configuration in both the east flow and the north flow design. An analysis of the effect of using 2 nm route widths rather than 1.5 nm route widths indicated that virtually no changes to the design would be necessary to accommodate the wider routes.

7.1.2 Denver

7.1.2.1 The Post-1982 Denver Terminal Area Design

The post-1982 Denver terminal area design for the west flow and east flow configurations are pictured in Figures 7.5 and 7.6. Both of these configurations comply with most of the features of the Task Force terminal area model described in Section 3. The design of the terminal maneuvering area in the east flow configuration is virtually identical to the Task Force model. The west flow configuration departs from the model slightly in order to accommodate the perpendicular runway utilization of the west flow (arrivals - 26L, departures-35). This design modification was accomplished by extending the right base to about 11 nm to permit the departures to have some maneuvering room to climb to 7500 feet and turn toward their low altitude departure fix. The location of the low altitude arrival and departure waypoints are unaffected by this design modification.

In the west flow configuration only the northbound departure route was tunneled under an arrival route. This restriction will not affect most aircraft as only aircraft with vertical gradients of 470 ft/nm or greater will need to restrict their climb. In the east flow configuration, the north and southbound departures are restricted to 10,000 ft or less within 7.5 nm of the departure waypoint. Aircraft with a climb gradient of 330 ft/nm or greater will be affected by this restriction. East and westbound traffic can depart the terminal area without altitude restrictions.

Enroute Connecting Points

With the predominant low altitude flow at Denver being in the north-south direction, the routes to the north, arrival 202 and departure 302, are considered to be low altitude routes and they tie into a common two way low altitude route at the periphery of the 45 nm terminal area. Similarly, to the south arrival route 205 and departure route 304 join together into a two way low altitude route to the south.

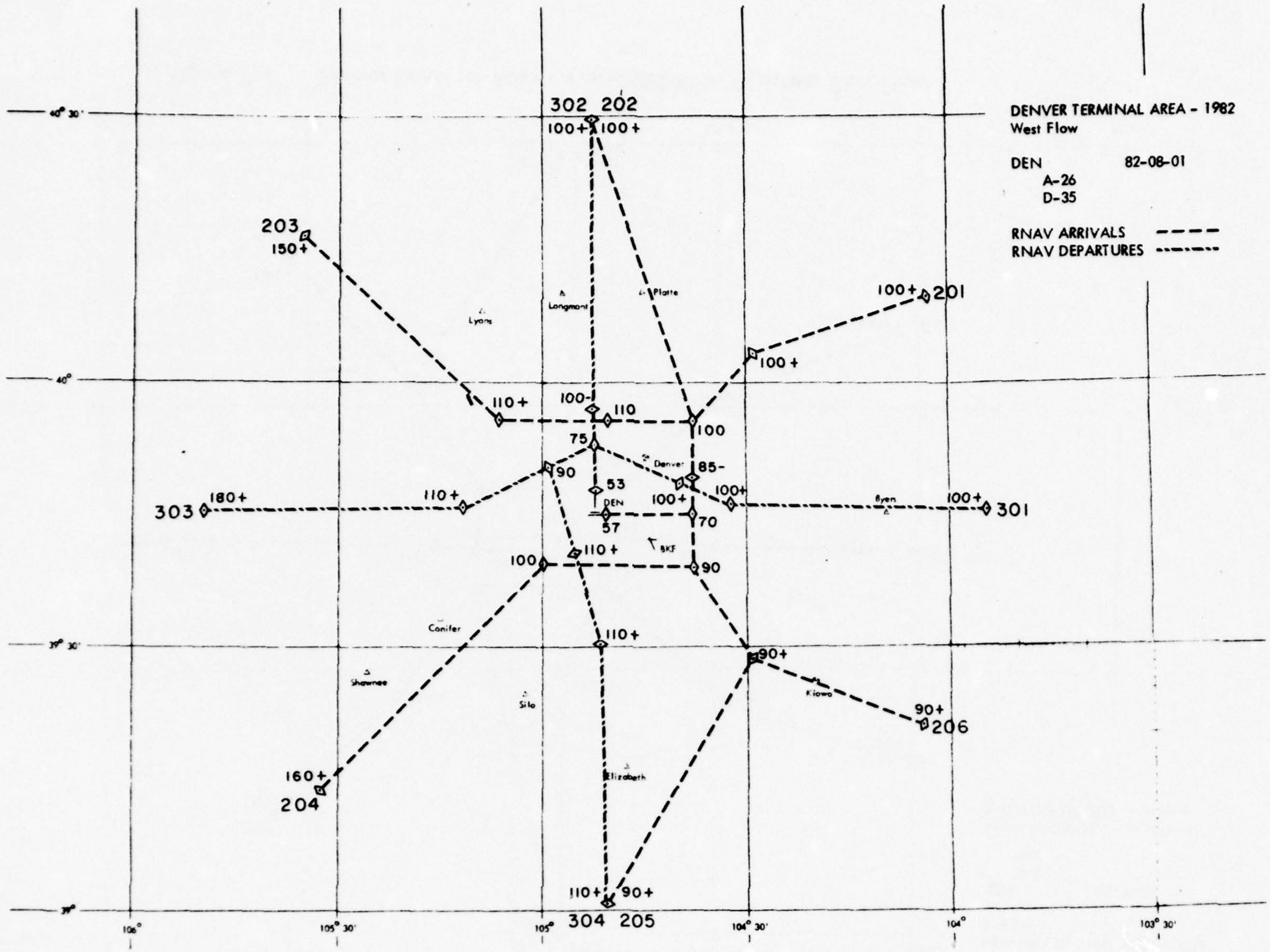


Figure 7.5 Denver Terminal Area - Post-1982 RNAV Routes, West Flow

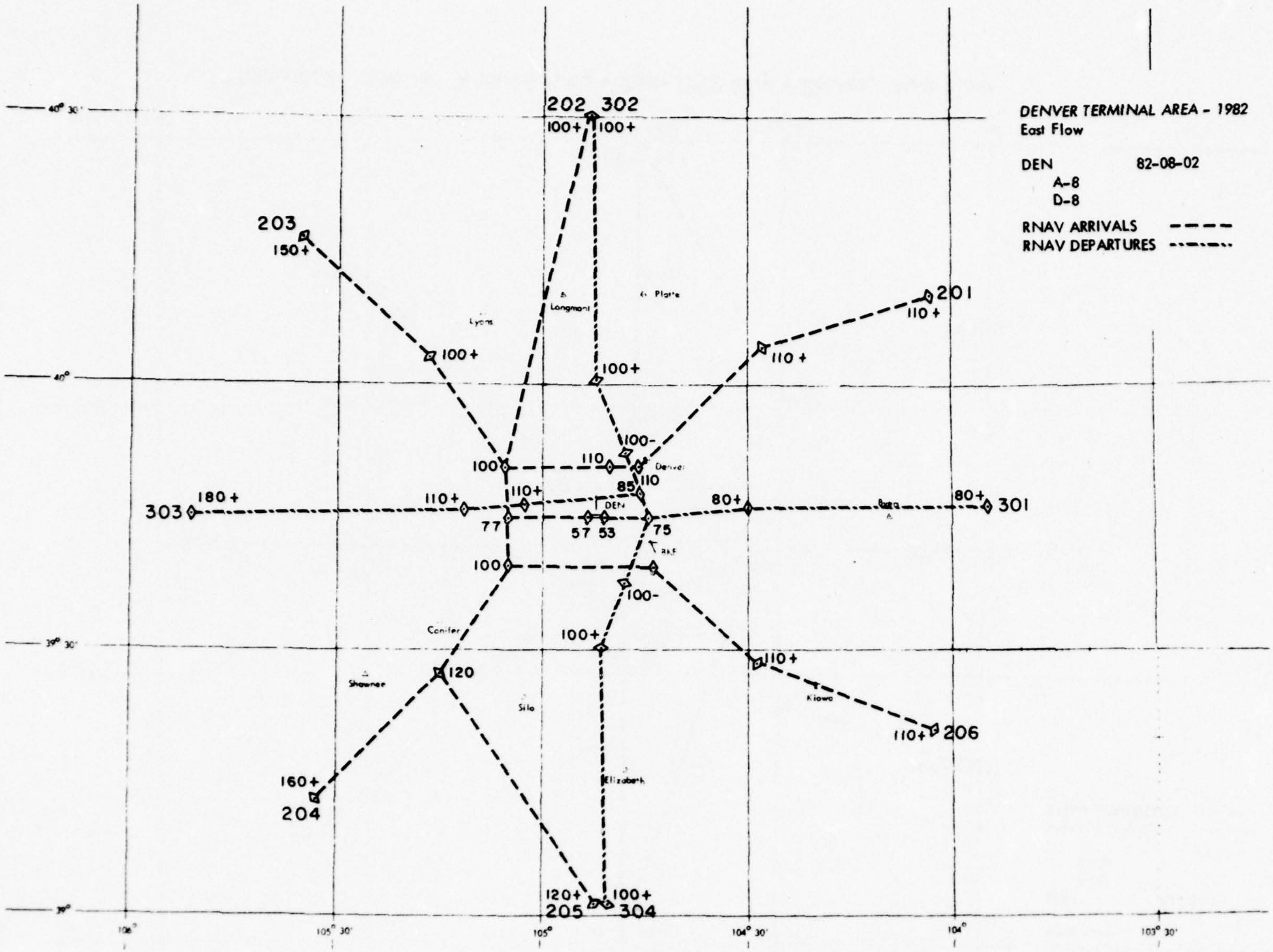


Figure 7.6 Denver Terminal Area - Post-1982 RNAV Routes, East Flow

The remaining routes were considered to be high altitude routes in the northeast, east and southeast directions and the northwest, west and southwest directions. The high altitude arrival routes were bent toward the east (routes 201 and 206) and west (routes 203 and 204) rather than proceed to the center of the octant. This was done to reflect the influence of the high altitude traffic distribution diagram for Denver.

7.1.2.2 The Post-1982 Task Force Concept at Denver

The post-1982 Denver terminal area designs are in general accord with the Task Force model. No changes were made from the model to develop the east flow design. In the west flow design the northern downwind leg was moved 5 miles to the north to permit eastbound departures on route 301 to gain sufficient altitude to clear the inbound traffic. In subsequent terminal designs situations like the eastbound departures were treated slightly differently. Rather than performing a 90° right turn, departures were routed in a 270° climbing left turn on route to the departure fix from where the route is as shown in Figure 7.5. The downwind leg would not have been moved north in this case. The New Orleans terminal area uses the 270° climbing turn technique. An analysis of using ± 2 nm route widths rather than the ± 1.5 nm used in the design indicated that almost no changes would be necessary in the 1982 terminal route structure.

7.1.3 Philadelphia

7.1.3.1 The Post-1982 Philadelphia Terminal Area Design

In the post-1982 Philadelphia terminal area design the octant flow patterns which were achieved in the 1977 design were retained. However, the location of several of the waypoints were changed to correspond to the location of the waypoints in the Task Force terminal area model. As a result, the terminal maneuvering area could be reconfigured and the octant terminal area configuration as described in Section 3 could be applied to the design. Figures 7.7, 7.8, 7.9 and 7.10 depict the resulting terminal design. The design has been developed for both the high and low altitude route structure. The enroute connecting points were obtained from the low altitude traffic distribution diagram. Each of the eight sectors which contained low altitude traffic are represented in the eight low altitude arrival and departure routes. Also, the arrival and departure routes merge into a two-way enroute structure at the connection points, 45 nm from the airport center. The low altitude arrival waypoints are located in the center of each arrival octant 25 nm from the airport center. Low altitude departure waypoints are located in the center of each departure octant at 15 nm from the airport center.

Arrivals from the downwind octants approach the airport from the low altitude arrival waypoint and enter a conventional downwind leg 5 nm offset from the runway, then intercept the base leg 5 miles from the IWP. The IWP is located 10 miles from the runway threshold as in the 1972 and 1977 designs. Traffic in upwind octants proceeds from the low altitude arrival fix to intercept the base leg at the same 5 nm point from the IWP as the other two octant arrivals. The downwind arrivals top the cross wind departures as these departures have insufficient time to climb to 6,000 ft. The upwind departures can climb without

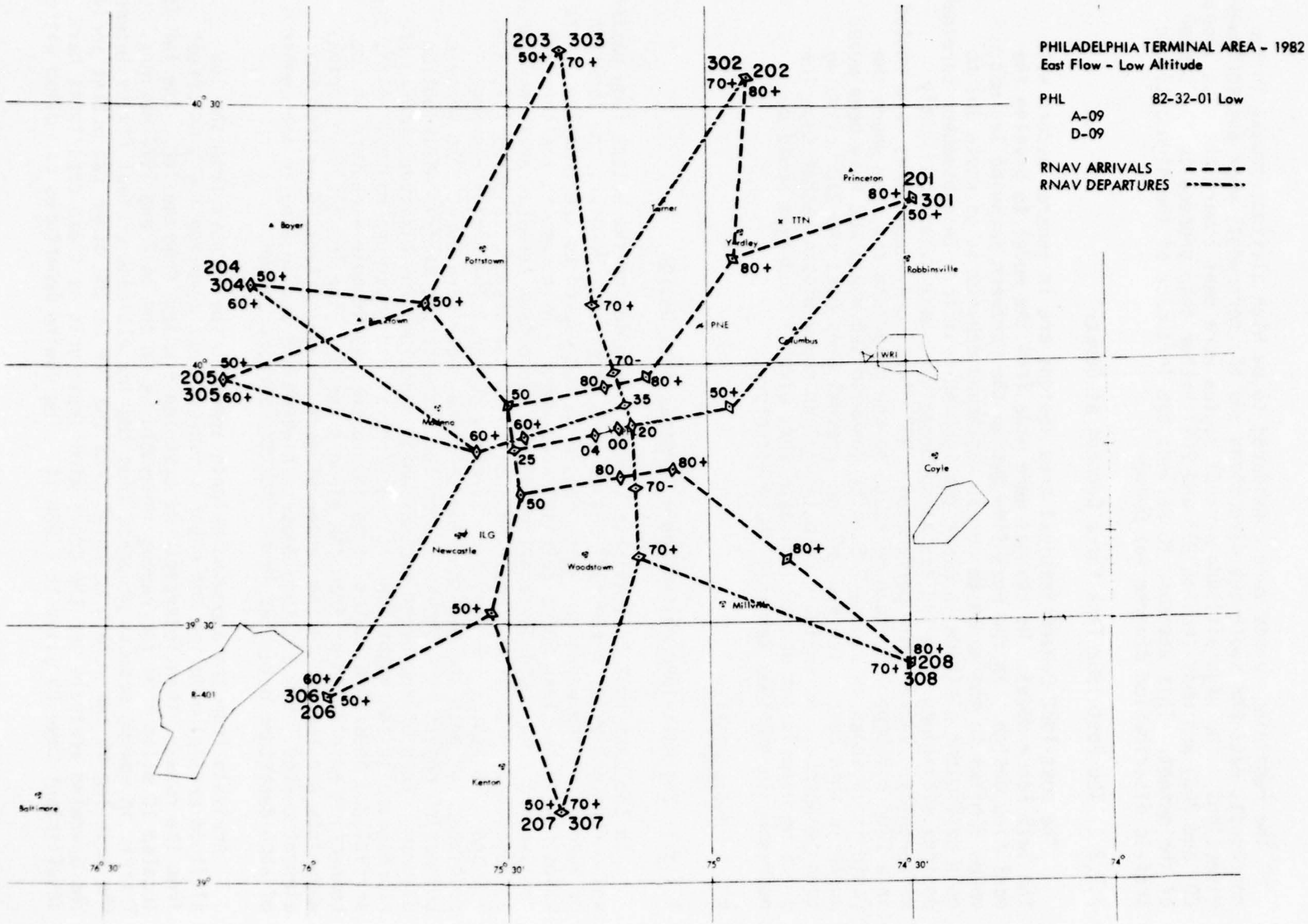


Figure 7.7 Philadelphia Terminal Area – Post–1982 Low Altitude Routes, East Flow

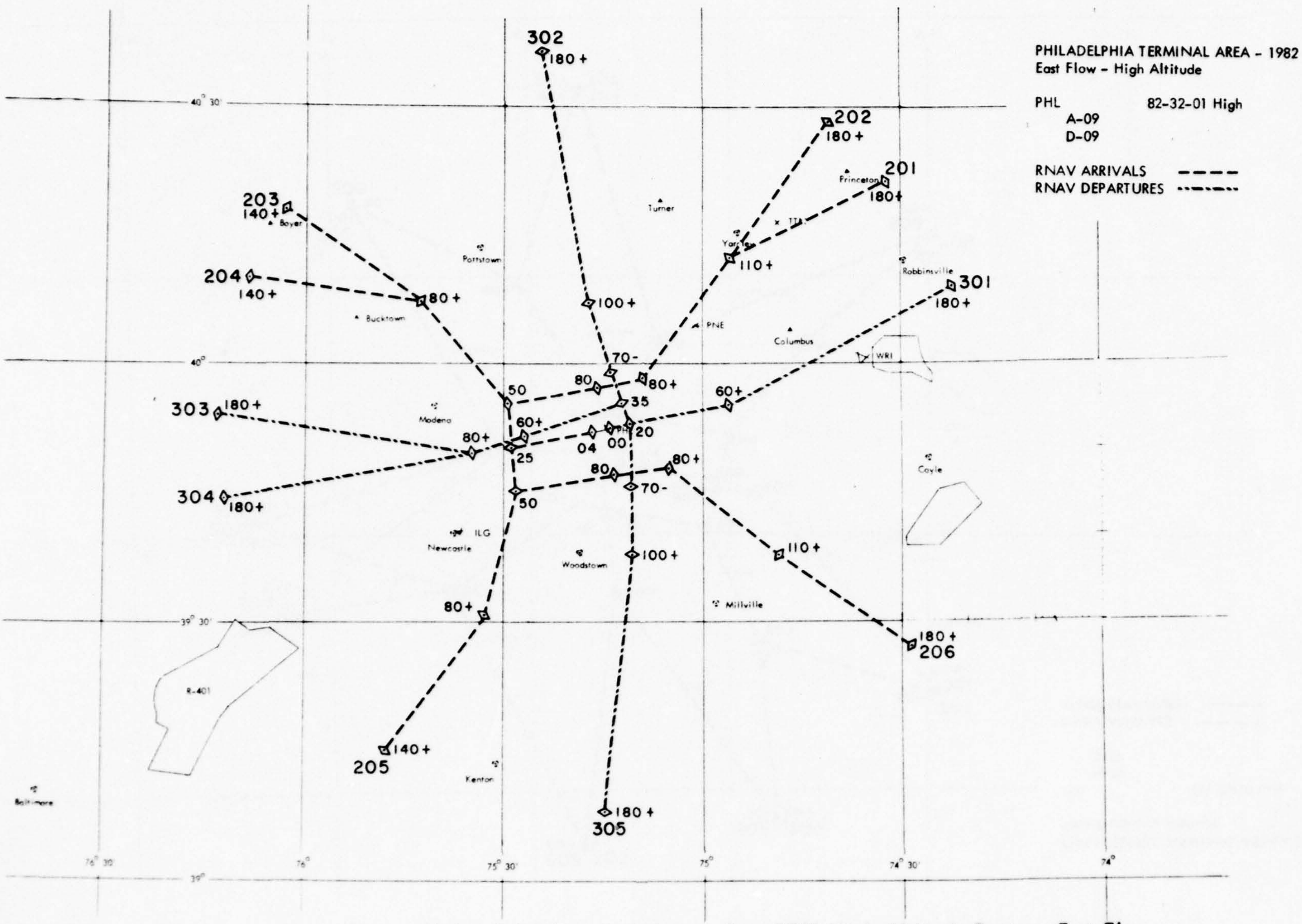


Figure 7.8 Philadelphia Terminal Area - Post-1982 High Altitude Routes, East Flow

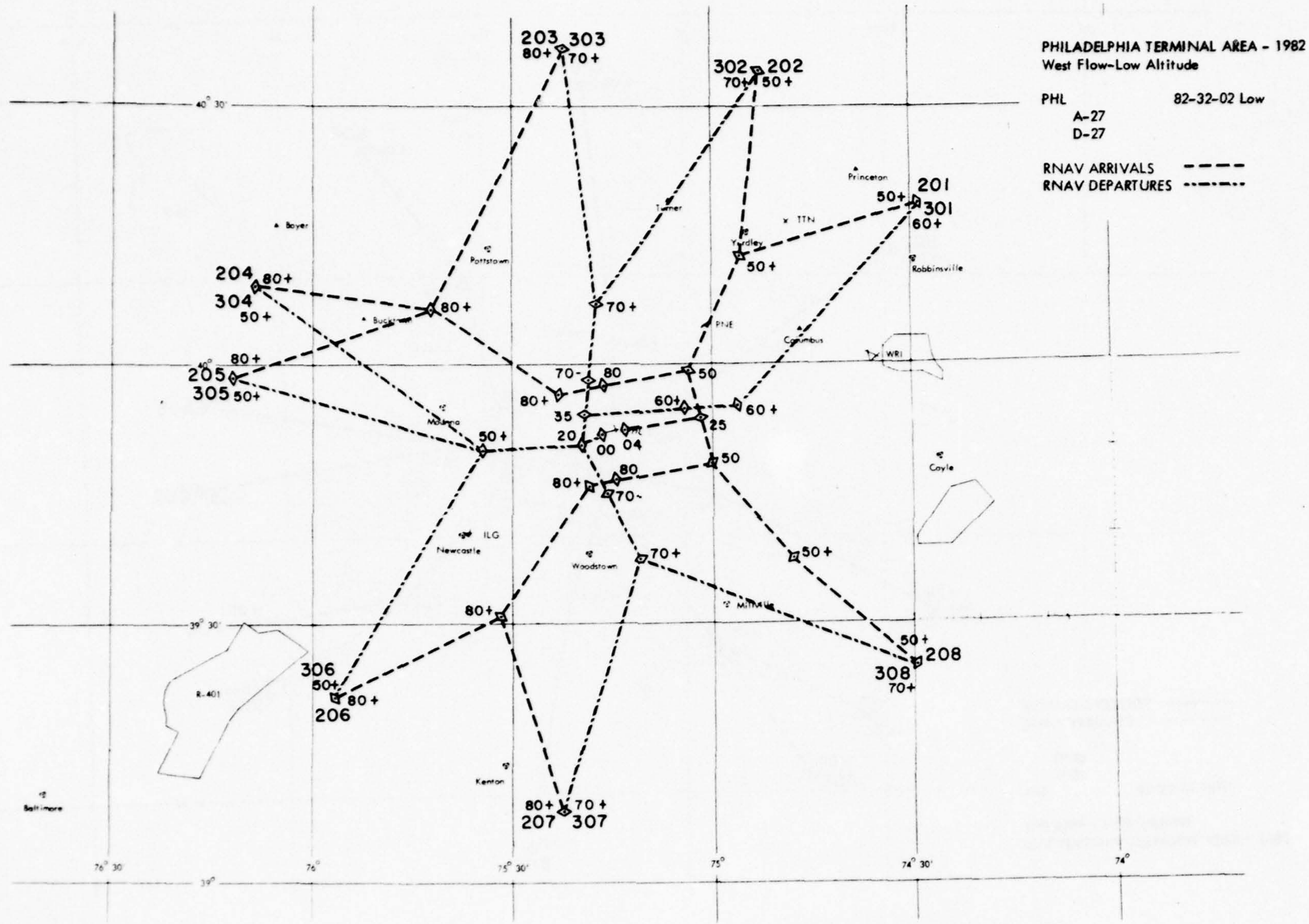


Figure 7.9 Philadelphia Terminal Area - Post-1982 Low Altitude Routes, West Flow

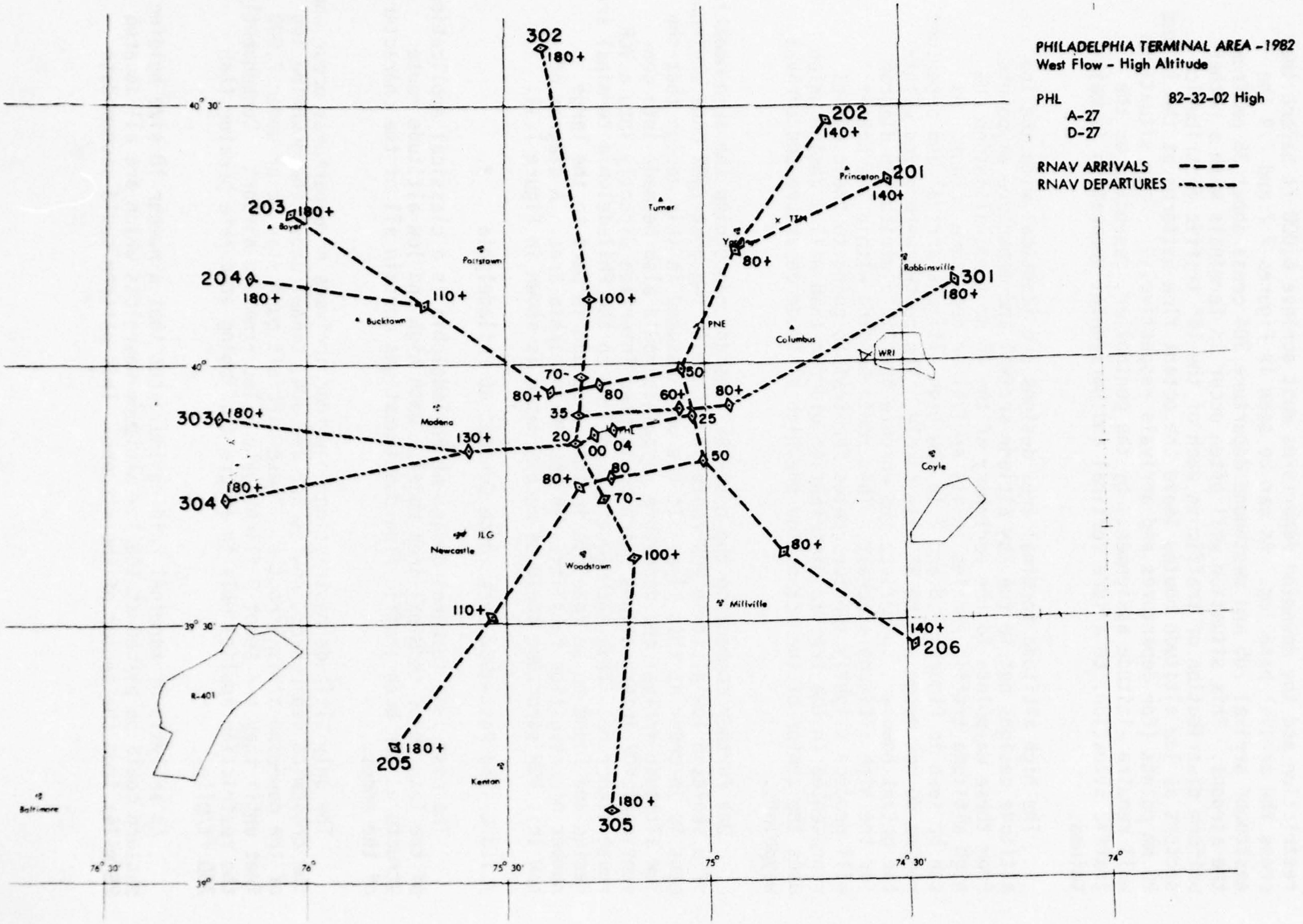


Figure 7.10 Philadelphia Terminal Area - Post-1982 High Altitude Routes, West Flow

restriction and the downwind departures must achieve 6,000 ft before they cross the arrival base leg. As can be seen in Figures 7.7 and 7.9 the eastbound arrival 205 and westbound departure 304 cross about 35 nm from the airport. This situation will often occur in terminals with a rather uniform distribution of traffic in each of the 15° traffic distribution sectors as low altitude routes leave the octant flow patterns at the 15 and 25 nm points (for departures and arrivals respectively). Such situations will require altitude assignments by the controller, depending on the traffic situation, to assure vertical and horizontal separation is maintained.

The high altitude terminal area designs are identical with the low altitude designs out to the low altiude arrival and departure waypoints. From these waypoints to the periphery of the 45 nm terminal design the high altitude traffic remains in its arrival or departure octant. As can be seen in Figures 7.8 and 7.10 the high altitude arrival and departure routes do not merge at the 45 mile circle. The routes were moved within the octant however, to reflect the enroute traffic distribution diagram for the high altitude aircraft. This route bending within the octant will produce slightly shorter routes for traffic going to those cities represented in the traffic distribution diagram than will a design which uses the center of the octant for the high altitude departure and arrival waypoints.

One further comment on the post-1982 designs concerning the accommodation of a skeleton low altitude VOR route structure in the post-1982 RNAV environment is in order at this time. It has been assumed in this design that the low altitude arrival and departure waypoints would also be made into conventional VOR intersections which would then interface directly into a VOR route structure. This technique was applied to the Philadelphia terminal area design and found to be feasible in this area due in part to the large number of navigation facilities in the Philadelphia area. A diagram of how this VOR structure could be accommodated is shown in Figure 7.11.

7.1.3.2 The Post-1982 Task Force Concept at Philadelphia

The post-1982 terminal design at Philadelphia is a classical application of the Task Force terminal area model. Both high and low altitude route structures for both traffic flow configurations contain all of the characteristics of the model.

The only altitude restriction on either arrivals or departures occur when the crosswind departures, routes 302 and 304, tunnel under the downwind leg of the downwind arrival routes. These aircraft must stay at or under 7,000 feet until they are about 9 flight path miles from the airport. Consequently, the restriction applies only to aircraft climbing at a rate greater than 750 ft/mile.

An analysis of terminal holding indicates that a number 10 size holding pattern could be placed at the low altitude waypoints which are all located 25 miles from the center of the airport. This pattern could accommodate

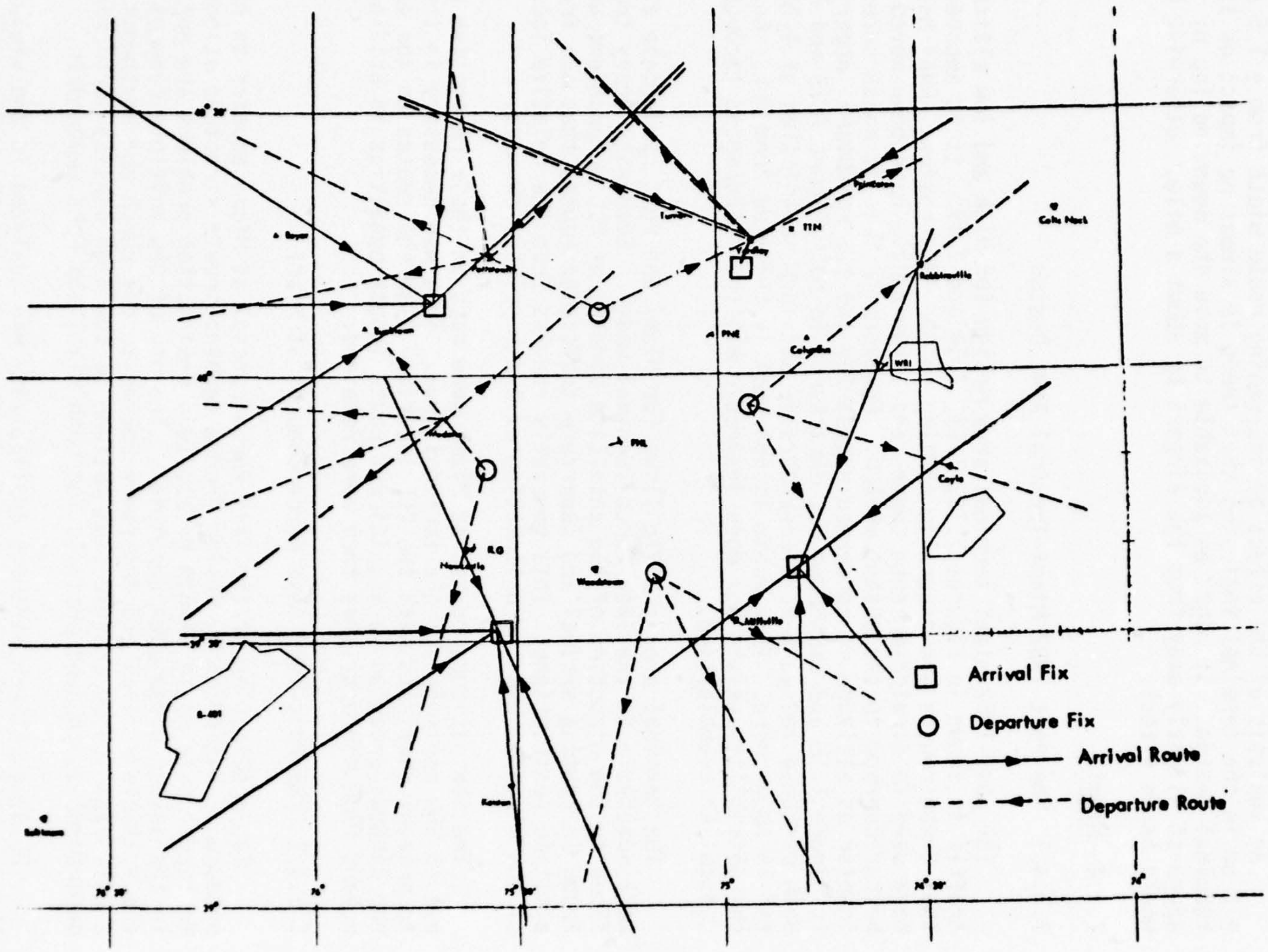


Figure 7.11 Philadelphia Skeleton VOR Airway Structure

aircraft from 9,000 to 14,000 feet at speeds up to 230 KIAS.

An analysis of the effect of increasing route width from ± 1.5 nm to ± 2 nm in the terminal indicates that there is almost no impact on the terminal design. It might be advisable to move the downwind leg of the approach slightly away from the airport by about a mile. Otherwise there would be no effect.

7.1.4 Miami

7.1.4.1 The Post-1982 Miami Terminal Area Design

The post-1982 Miami terminal area design for high and low altitude traffic is shown in Figures 7.12, 7.13, 7.14 and 7.15. It is apparent that these routes are generally similar to the 1972 routes. RNAV has been used to straighten some routes and a few routes have been moved to better conform to the octant design. However, traffic is again unrestricted insofar as altitude is concerned except for the FLL westbound departures in Figure 7.15 and eastbound FLL departures in both Figure 7.13 and 7.15. Both of these routes have a considerable altitude restriction of 5,000 ft for 45 nm or more. This route is not heavily traveled from FLL. Consequently, the possibility exists for more desirable altitude clearances through controller coordination.

The terminal area traffic flows for Miami and Fort Lauderdale are very well adaptable to the Task Force terminal model. Even with heavy traffic flows in the direction of the satellite airport at FLL no problems are found in routing arrival and departure traffic on routes that are free of altitude restrictions. This generally results from the relative location of the airports and the orientation of their primary runways.

The low altitude routes at Miami were kept in their respective octants out to the perimeter of the terminal area. This was necessary in the north to prevent conflicts with the FLL traffic. Also the routes to the east to the Bahamas produced no significant route length penalties in abiding by the octant flow concept, thus they were retained.

7.1.4.2 The Post-1982 Task Force Concept at Miami

The application of the Task Force concept at Miami appears to have produced a satisfactory design from a terminal route structure standpoint. No large scale route length or altitude restriction problems are apparent in the design based upon the model. The use of the multiple runways and the multiple arrival and departure routes to the north and northwest provides a well distributed traffic flow pattern to the high density northbound departures-southbound arrivals for both Miami and Fort Lauderdale.

Holding pattern airspace availability was analyzed in the vicinity of the low altitude arrival waypoints which are located 25 nm from the center of the Miami airport. No difficulty in providing holding airspace up to 14,000 ft at these locations was found. Independent holding areas could be used in the northwest arrival octant for the waypoints near Westland

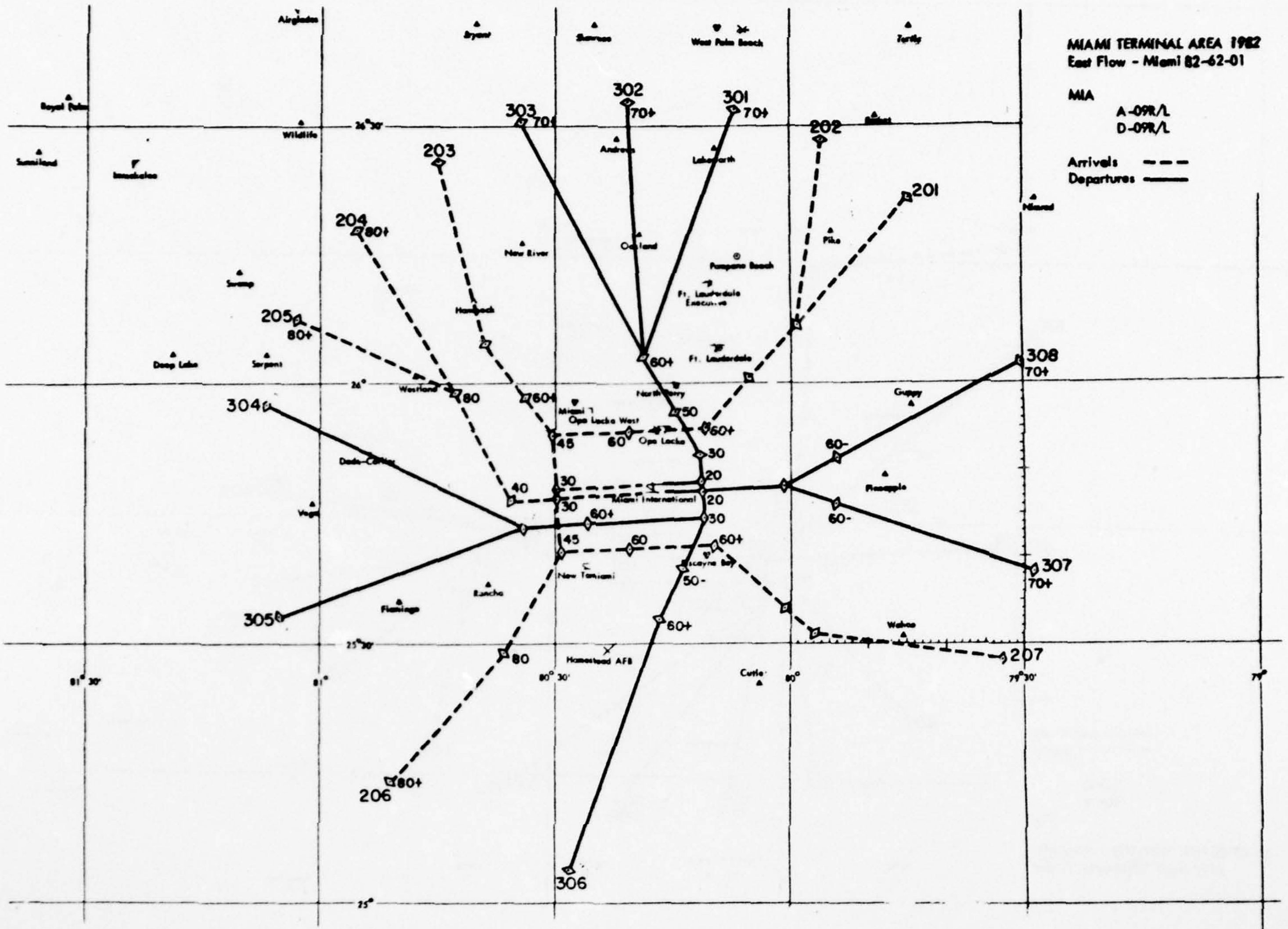


Figure 7.12 Miami Terminal Area - Post-1982 RNAV Routes, Miami, East Flow

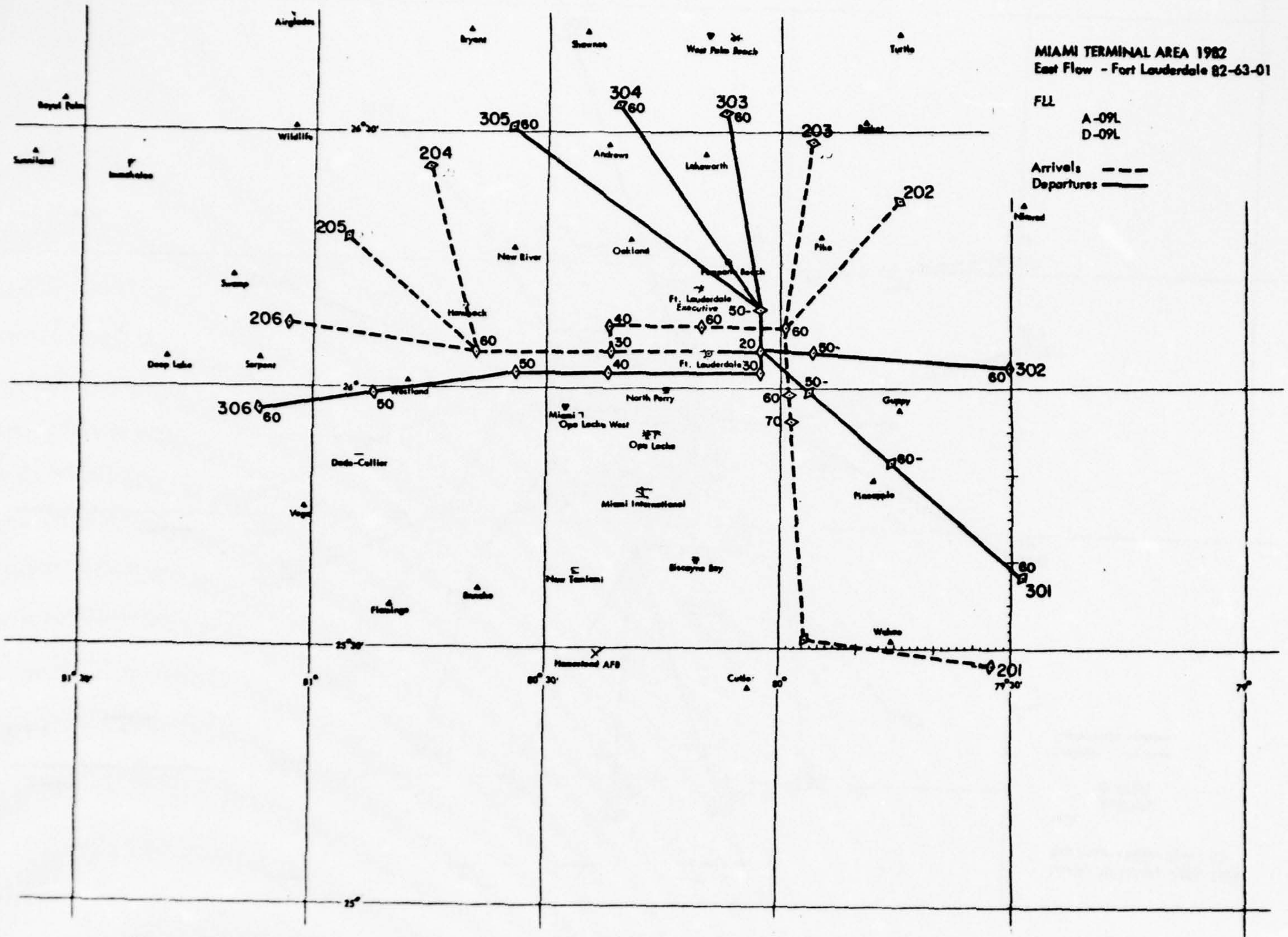


Figure 7.13 Miami Terminal Area - Post-1982 RNAV Routes, Ft. Lauderdale, East Flow

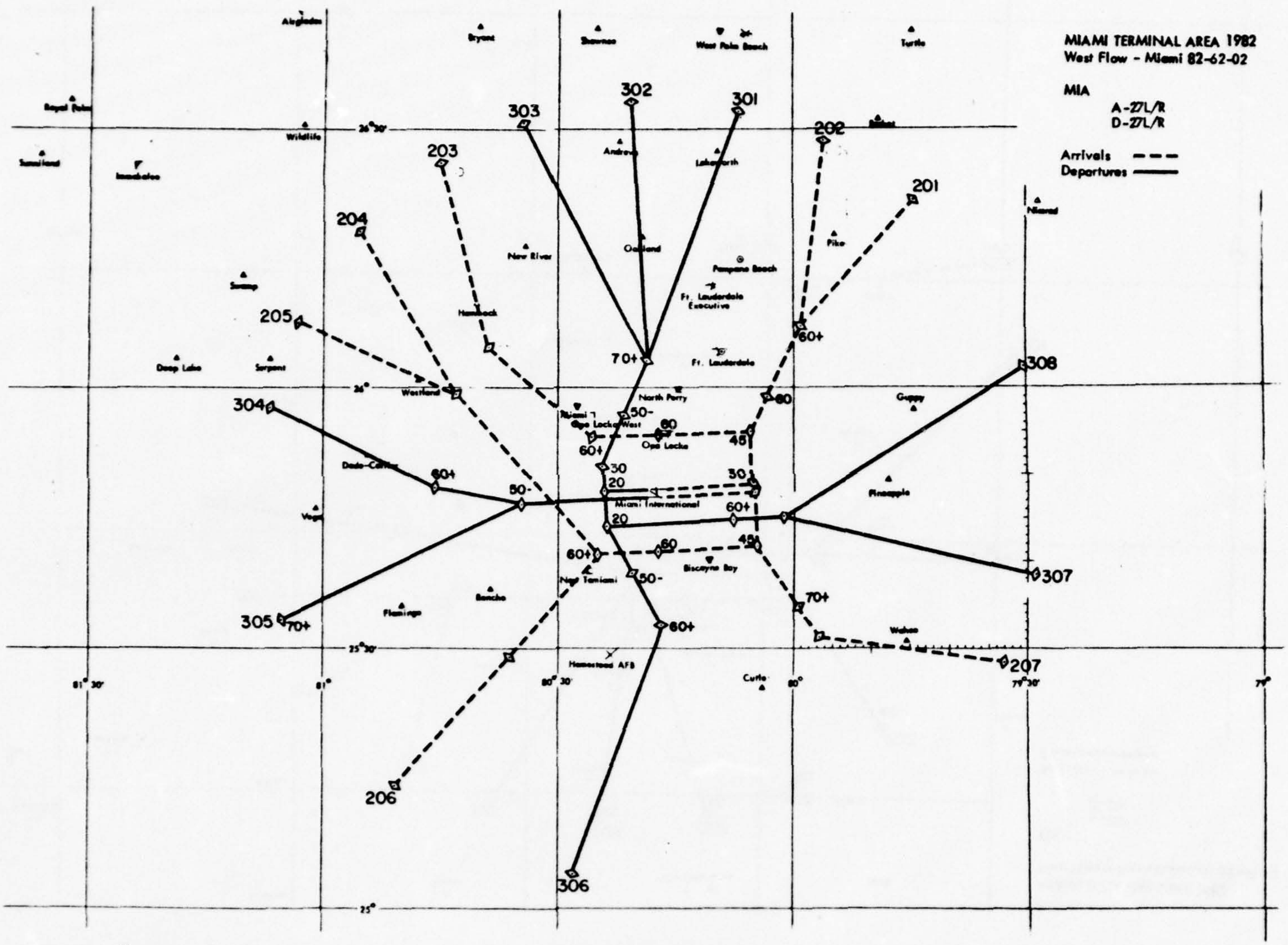


Figure 7.14 Miami Terminal Area - Post-1982 RNAV Routes, Miami, West Flow

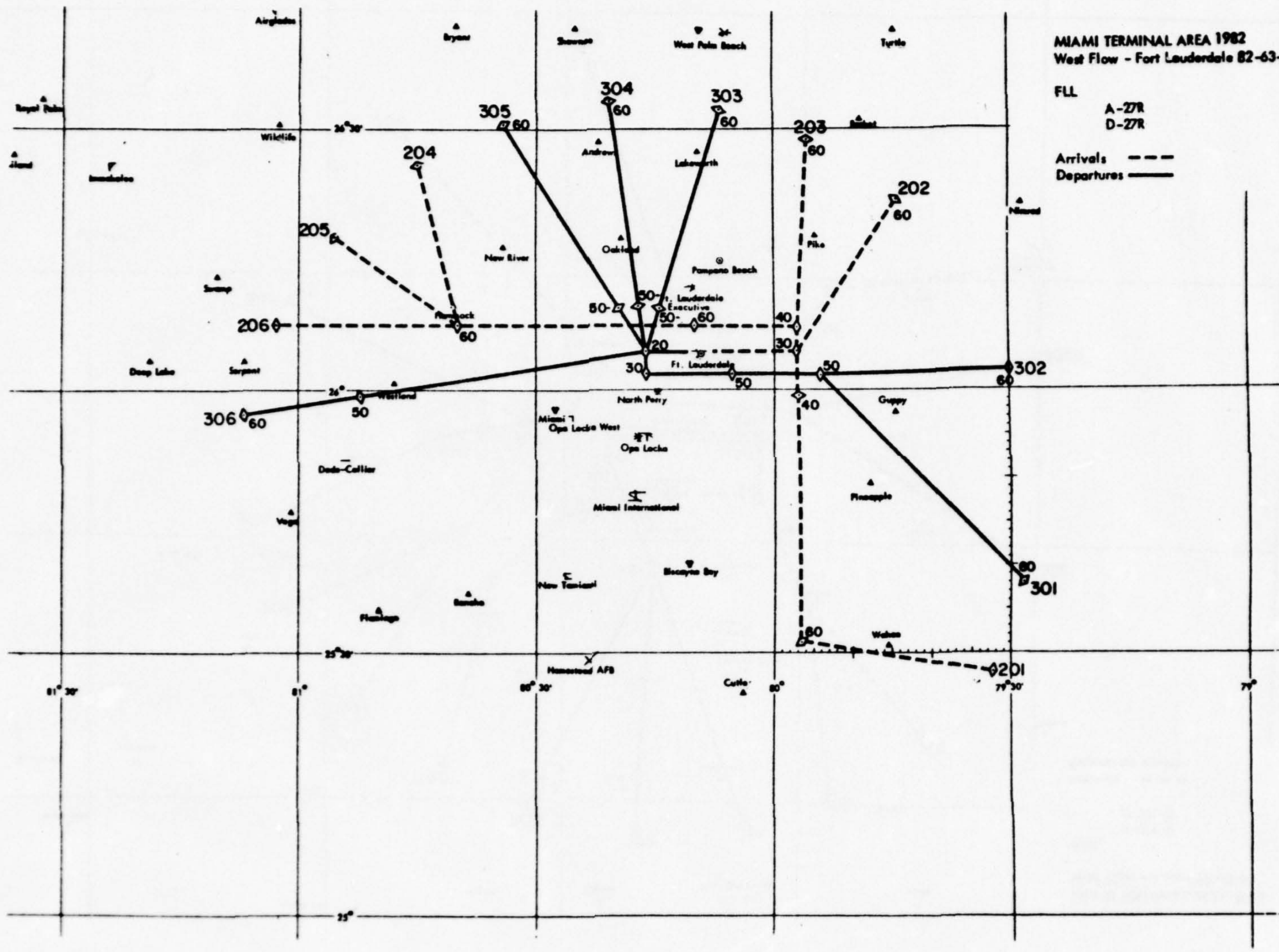


Figure 7.15 Miami Terminal Area - Post-1982 RNAV Routes, Ft. Lauderdale, West Flow

and Hammock.

While ± 1.5 nm route widths were used in these designs, there also appears to be no reason why ± 2 nm route widths could not be used to develop the post-1982 Miami route structure. Sufficient airspace is available for the use of parallel offset maneuvers even with the wider route spacings.

7.1.5 San Francisco

7.1.5.1 The Post-1982 San Francisco Terminal Area Design

The post-1982 designs for the San Francisco terminal area are shown in Figures 7.16 to 7.21. Several observations can be made concerning these designs.

Task Force guidelines cannot be followed in some instances due to the presence of several major airports in addition to the satellite airports. The octant concept, however, was used without appreciable effect on enroute flow. Arrivals from the south were routed farther west and departures in the same direction were routed farther to the east. Eastbound departures from SFO and OAK depart the terminal area farther north than present traffic but this does not result in appreciable disadvantage to aircraft operators.

Task Force design procedures are not possible on all routes due to high terrain, proximity and relative location of major airports, and the reduction in operation rates at SFO and OAK during southeast flow due to interaction of operations between the two airports.

The 1982 plans assumed increased traffic at SJC and OAK, therefore discrete routes for traffic at each airport were established where needed when possible.

<u>The West Flow Configuration (Figures 7.16, 7.17 and 7.18)</u>

San Jose arrival traffic from the north was routed near the perimeter of the terminal area to prevent climb and descent restrictions for SFO and OAK. Northbound SJC departures were routed so as to cause a minimum of restriction to other traffic. Arrival and departure routes of SJC to and from the east have less than optimum locations due to high terrain.

<u>The Southeast Flow Configuration (Figures 7.19, 7.20 and 7.21)</u>

SFO landing Runway 19 and OAK landing Runway 11 results in an incompatible flow of arrival traffic in the area.

San Jose terminal maneuvering area was restricted to the west side of the localizer in order to leave the east side available for SFO, OAK and SJC departures. (SJC departures must climb without restriction on the east side due to terrain.)

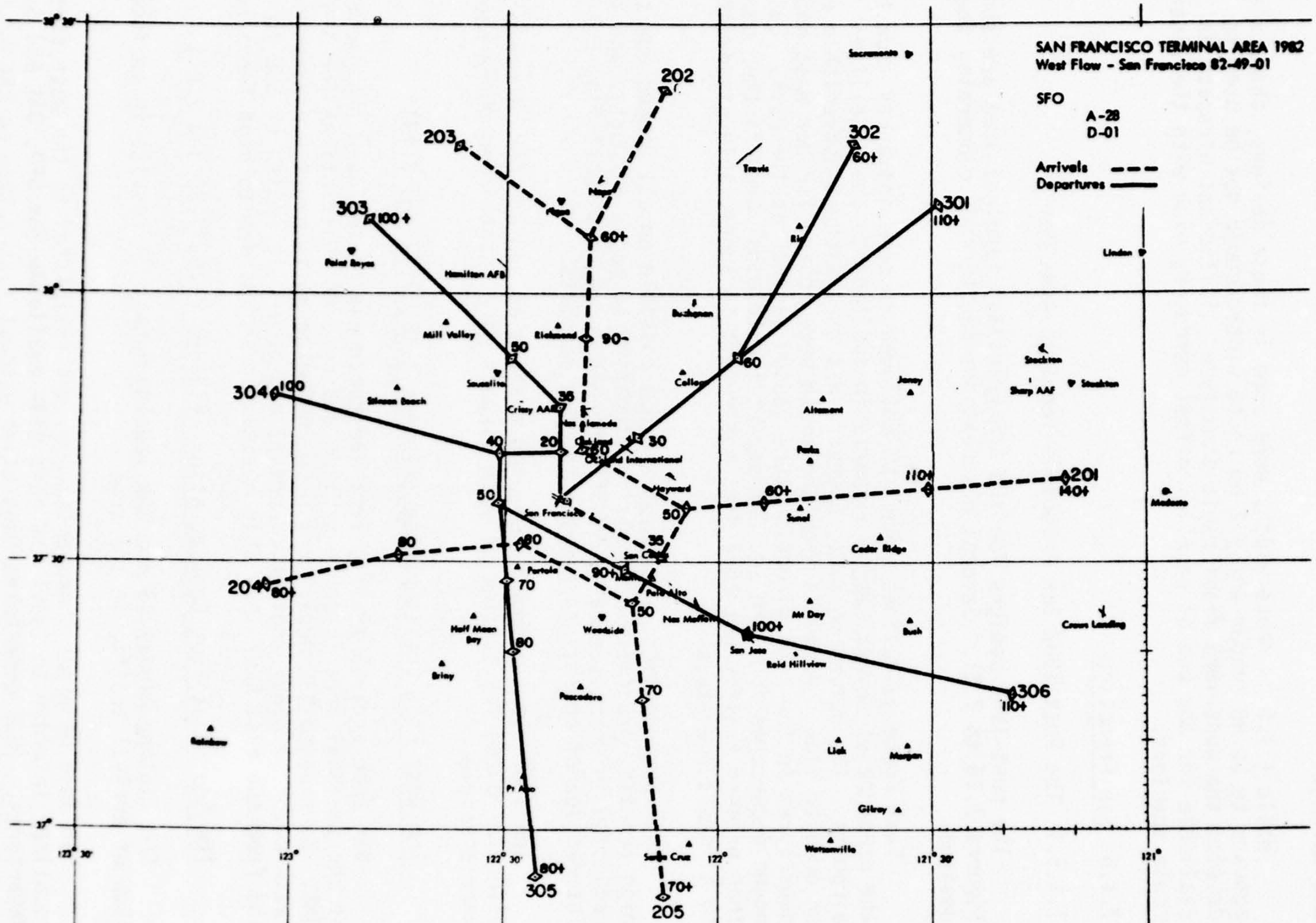


Figure 7.16 San Francisco Terminal Area - Post-1982 RNAV Routes, San Francisco, West Flow

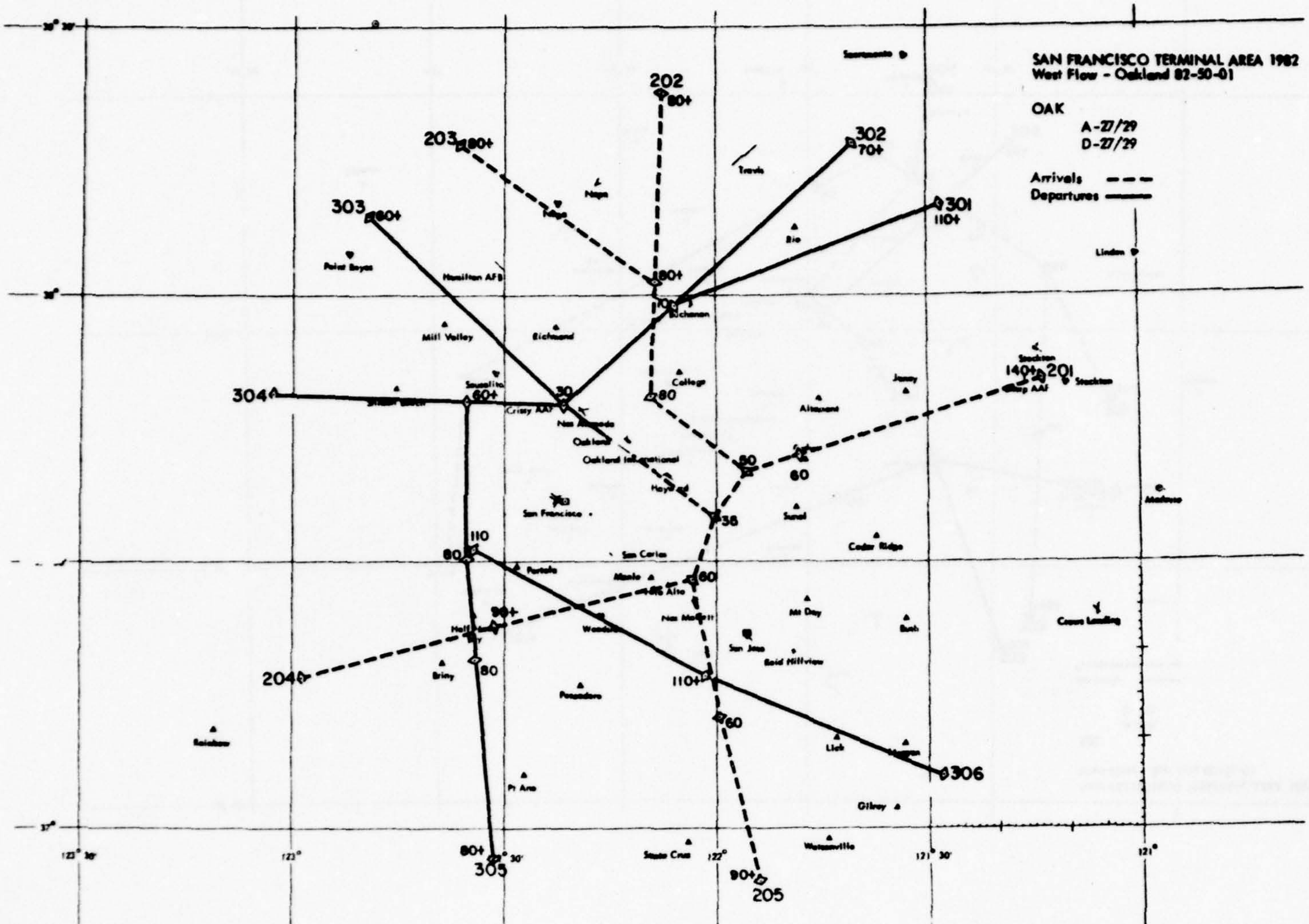


Figure 7.17 San Francisco Terminal Area - Post-1982 RNAV Routes, Oakland, West Flow

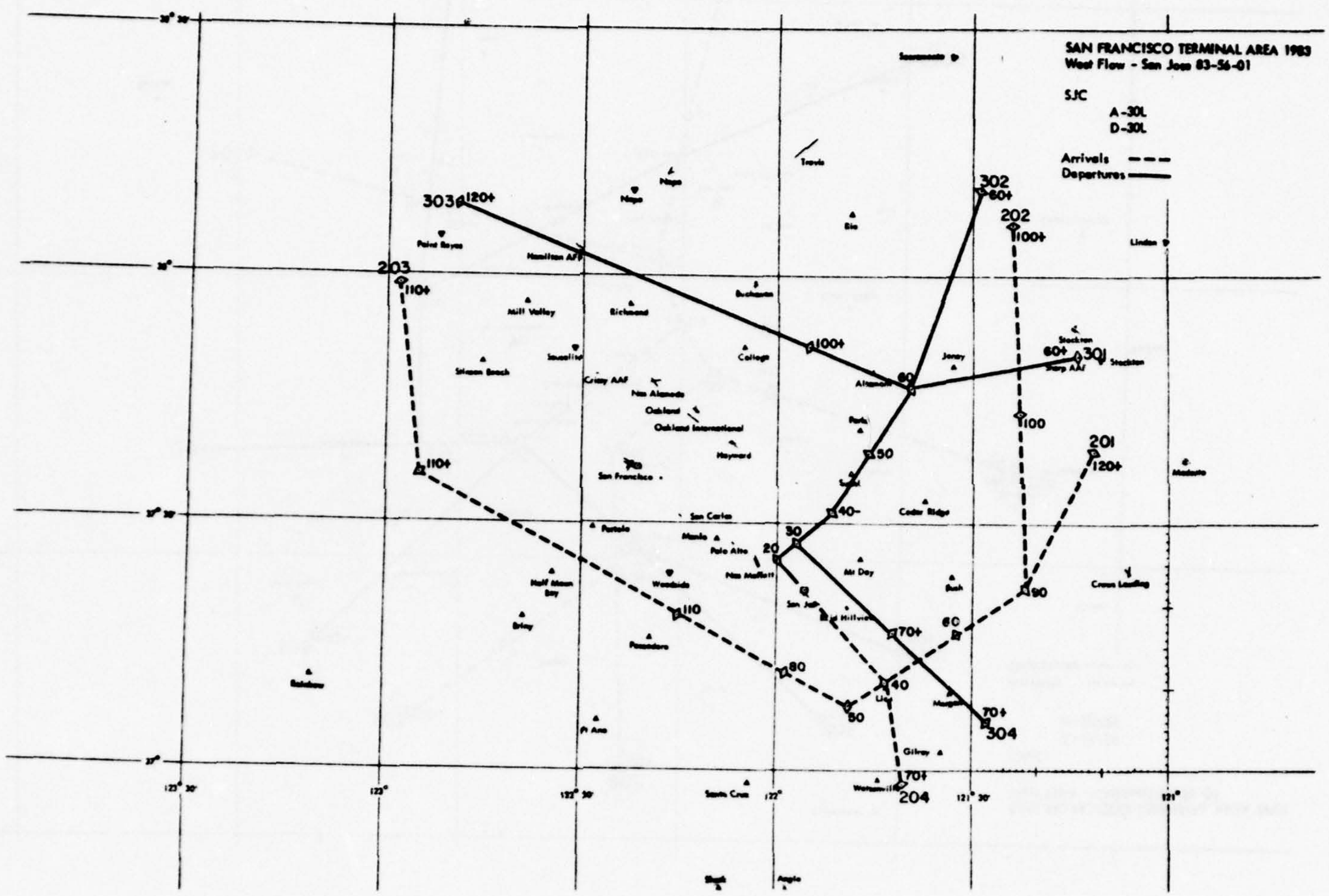


Figure 7.18 San Francisco Terminal Area - Post-1982 RNAV Routes, San Jose, West Flow

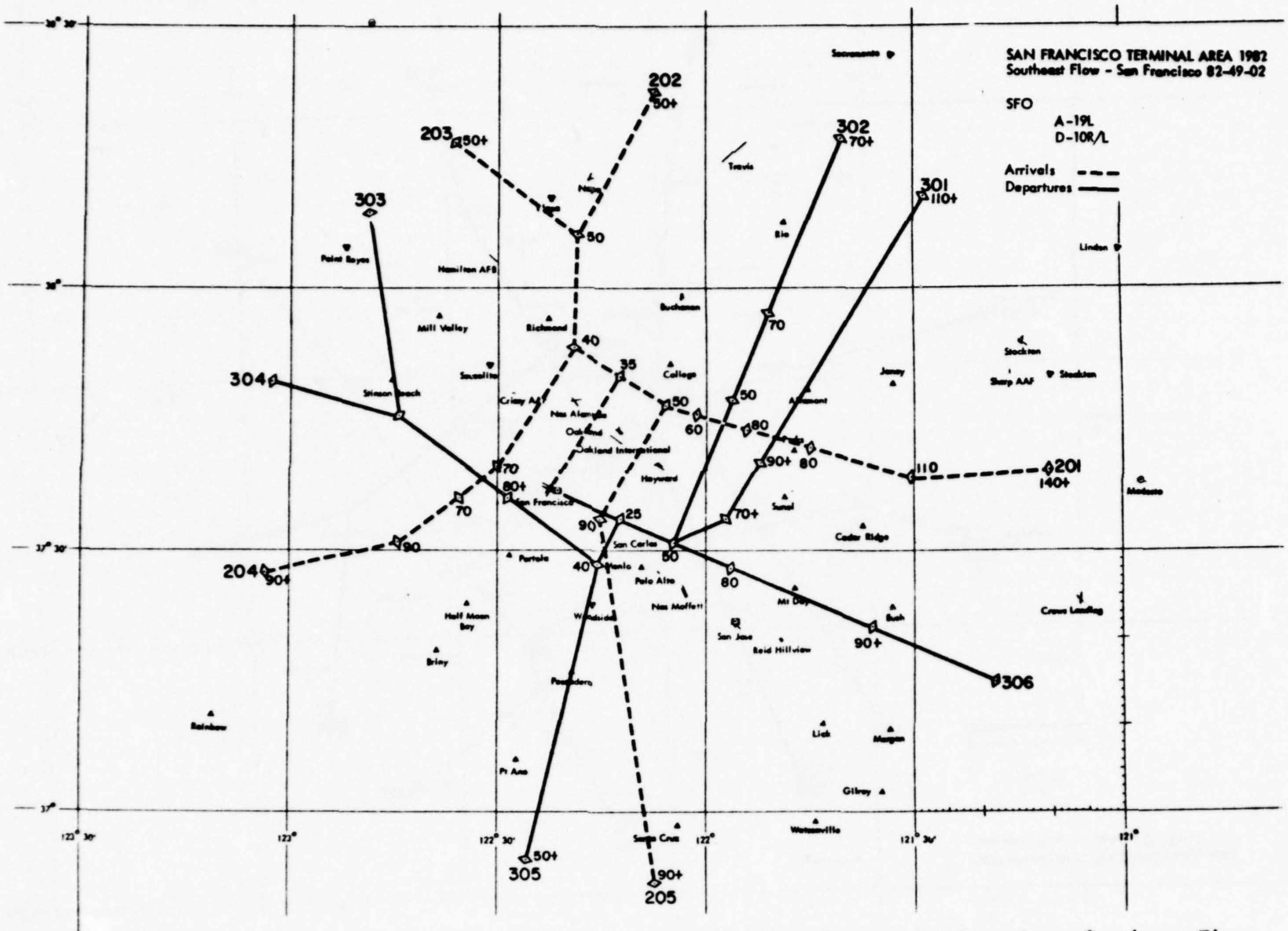


Figure 7.19 San Francisco Terminal Area - Post-1982 RNAV Routes, San Francisco, Southeast Flow

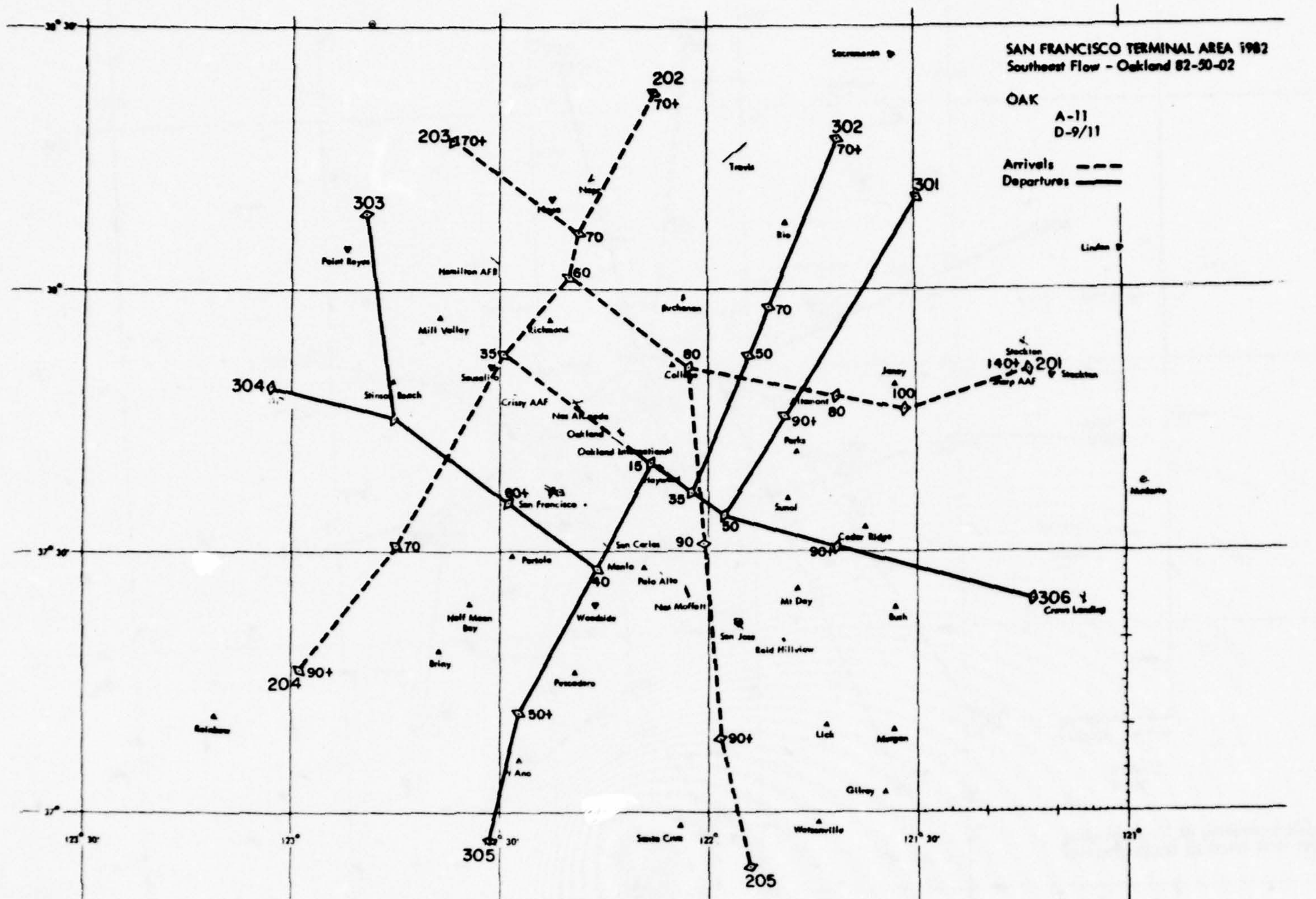


Figure 7.20 San Francisco Terminal Area - Post-1982 RNAV Routes, Oakland, Southeast Flow

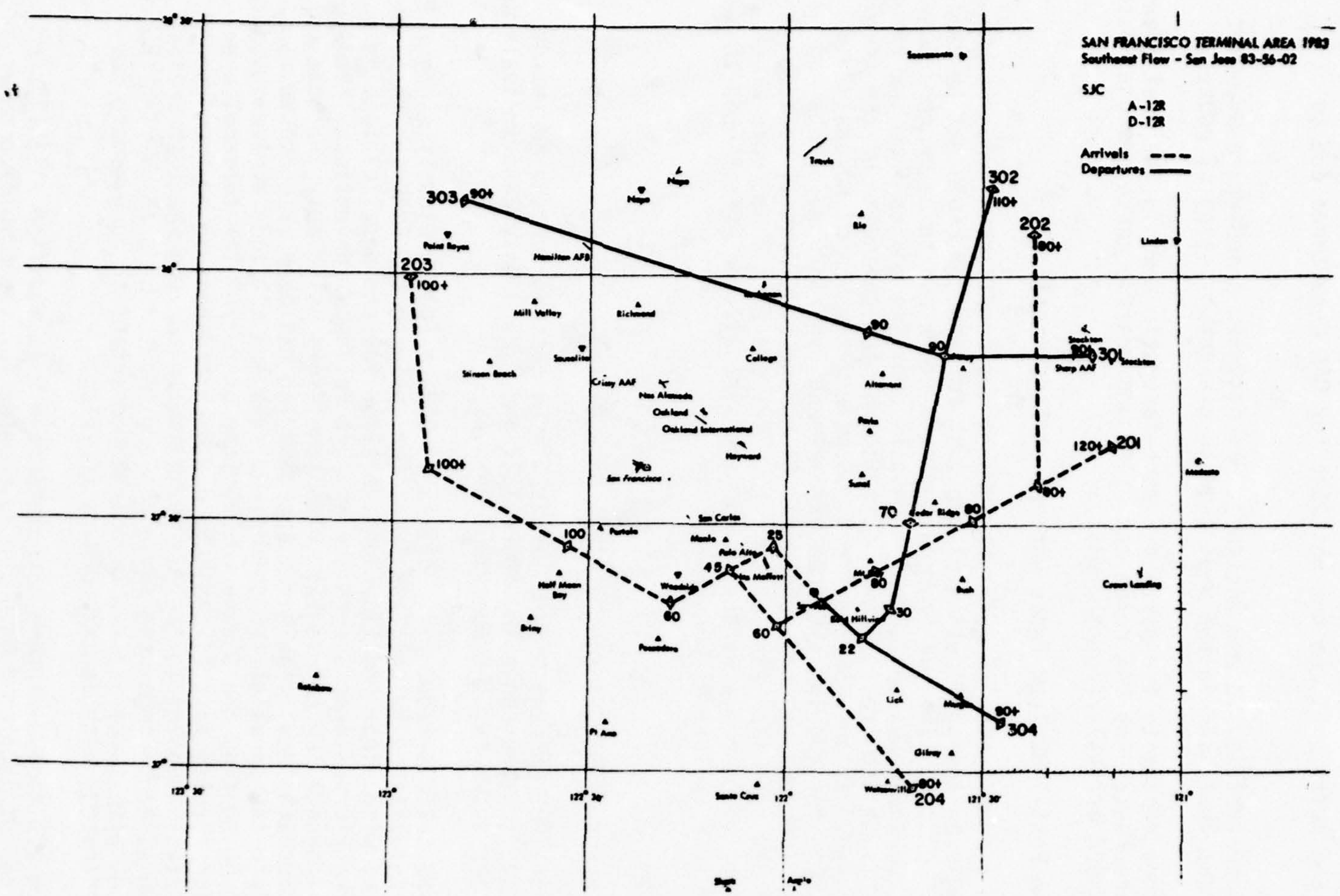


Figure 7.21 San Francisco Terminal Area - Post-1982 RNAV Routes, San Jose, Southeast Flow

Immediate left turns are not possible for OAK departures due to terrain.

Departure traffic, in one instance, was assigned a departure waypoint different from that used in the west flow to prevent crossing of routes.

Departure routes to the south are more favorable than in the west flow but departure routes for OAK north and eastbound traffic cause descent restrictions for OAK and SFO arrivals from the east.

7.1.5.2 The Post-1982 Task Force Concept at San Francisco

Due to a combination of multiple airport and conflicting runway problems at San Francisco, the application of the Task Force model could not be used to any great extent. The San Francisco flow pattern had to be changed considerably from the model configuration due to crossing routes from the three major airports in the area. The enroute flow at the perimeter of the terminal area was designed in an octant pattern. However, the use of nominal Task Force locations for the low altitude arrival and departure waypoints and the terminal maneuvering area routes had to change considerably to accommodate the complex San Francisco flow of traffic. The use of $\pm$ 2 nm route widths rather than $\pm$ 1.5 nm route widths would have virtually no effect upon the terminal route structure at San Francisco.

7.1.6 Chicago

7.1.6.1 The Post-1982 Chicago Terminal Area Design

The post-1982 Chicago O'Hare terminal area designs for the southwest flow and west flow are shown in Figure 7.22 and 7.23. Only RNAV arrivals and departures are shown for the post-1982 design.

The RNAV traffic flows for arrivals at O'Hare follow closely along the guidelines established by the Task Force for applying the RNAV design to a terminal area with minor modifications to allow for the parallel landing runways. Traffic patterns around the airport follow a conventional downwind-base-final approach leg combination with some flows using only the base and and final approach legs. The final approach leg has been extended to 15 nm to accommodate the parallel ILS operation. The low altitude arrival waypoints are located 30 nm from the O'Hare VORTAC (the center of the terminal area design) which results in a flight path distance of about 35 nm from the low altitude arrival waypoint to the runway threshold for the shortest arrival route. High altitude departure waypoints are located on a 45 nm ring from O'Hare VORTAC with three arrival waypoints per octant to accommodate the evenly distributed, high density O'Hare traffic.

The low altitude departure waypoints have been modified slightly from the guidelines of Section 3 in order to provide for the complex runway structure at O'Hare and to route departures away from Midway arrivals and departures. This modification resulted in departure waypoints which shift with the runway in use rather than being fixed as described in Section 3. The departure waypoints were all located within 15 nm of the O'Hare VORTAC.

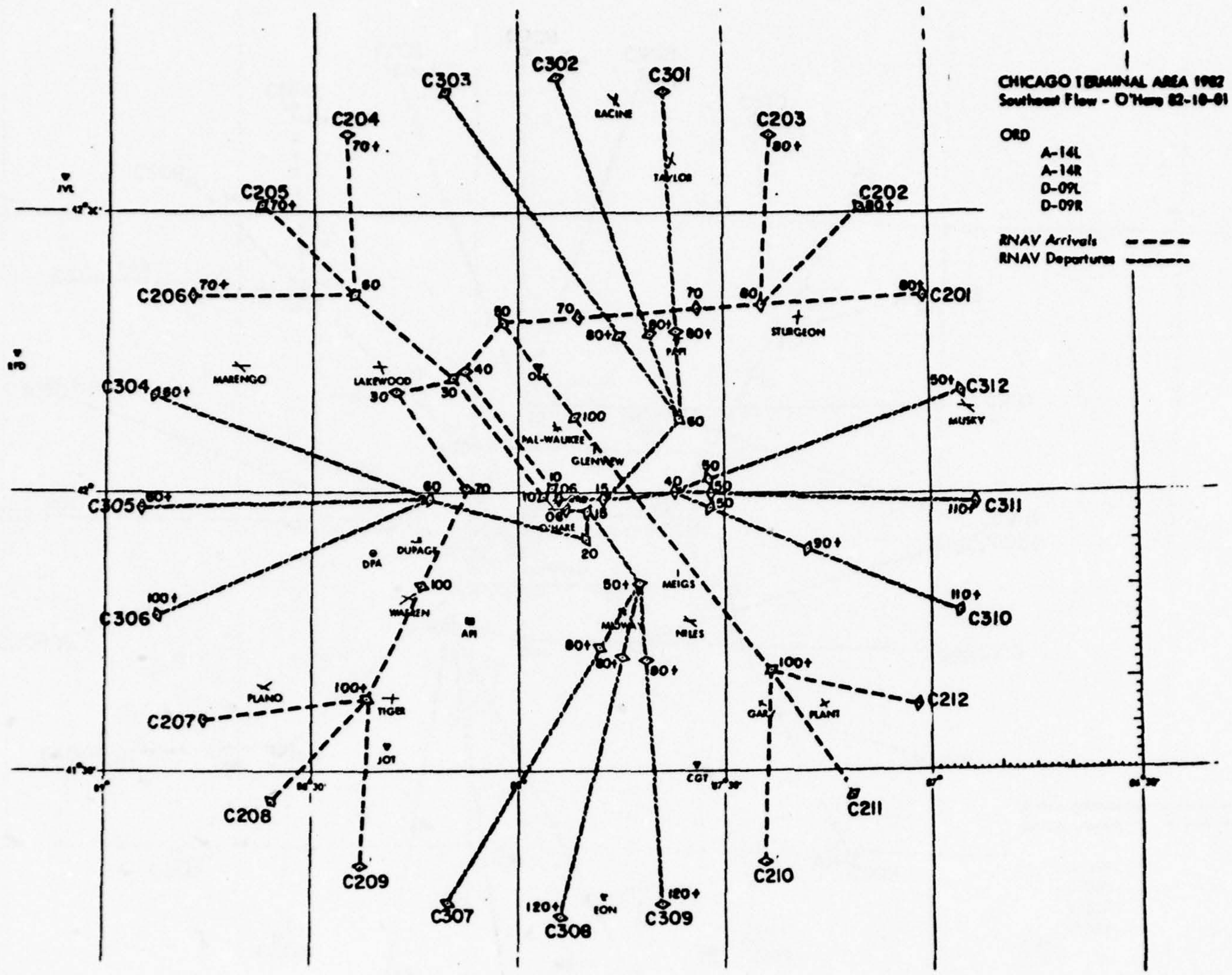


Figure 7.22 Chicago Terminal Area - Post-1982 RNAV Routes, O'Hare, Southeast Flow

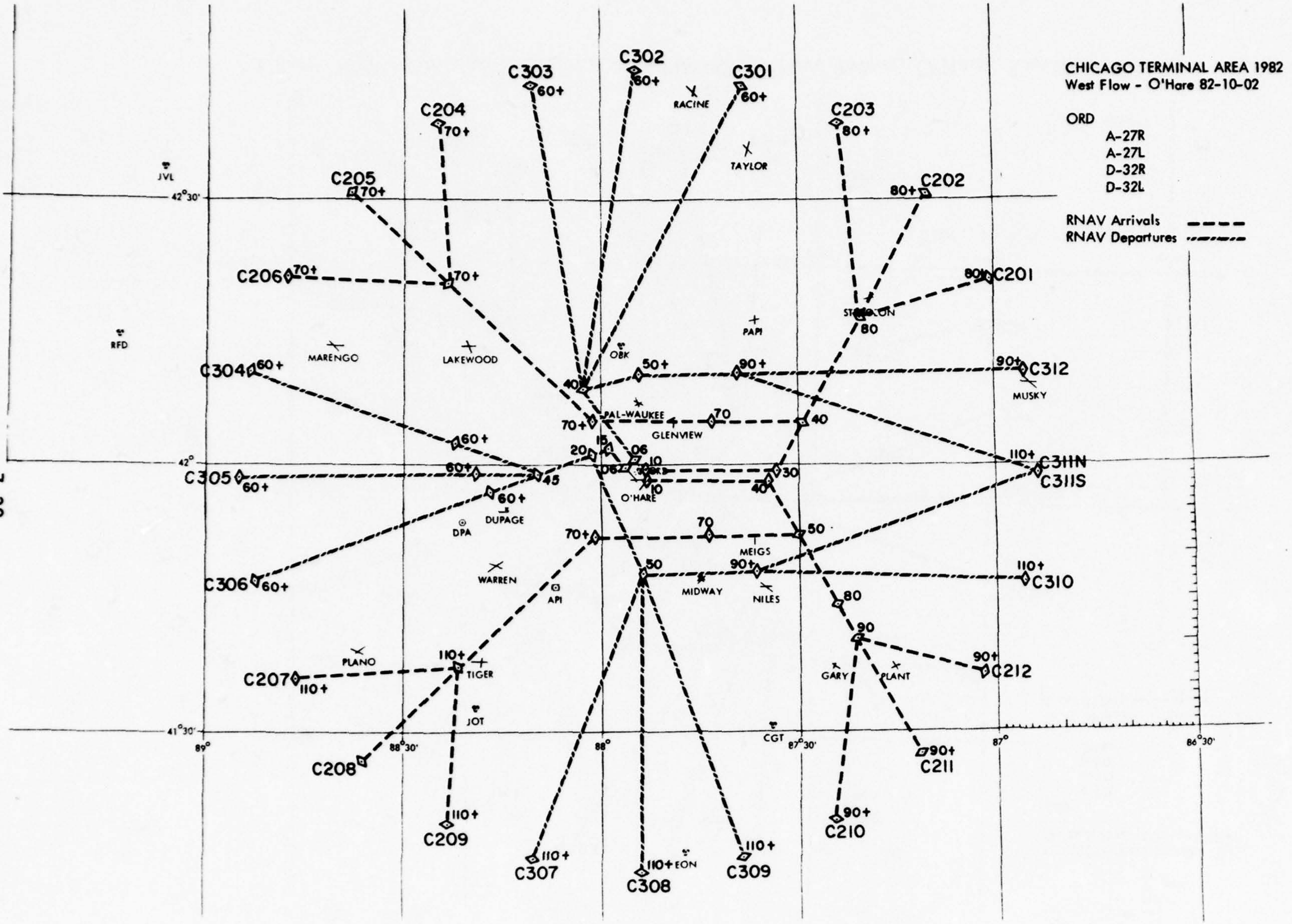


Figure 7.23 Chicago Terminal Area-Post-1982 RNAV Routes, O'Hare, West Flow

The high altitude departure waypoints are located in departure octants on the 45 nm ring with three routes per octant. In order to demonstrate some of the flexibility of the 1982 design, departure route C311 was given a north branch, C311N, for departures from Runway 32R or a south branch, C311S, for departures from Runway 32L.

In the Chicago terminal area, low altitude departures and arrivals are required to remain in their respective octants rather than diverge and go cross-grain to the octant pattern outside of the low altitude arrival or departure fix. This flow pattern was established for the low altitude routes in order to prevent interference with the Midway traffic patterns which are often using the airspace beneath the O'Hare traffic.

Midway traffic for the southeast flow and west flow (O'Hare operations) are shown in Figures 7.24 and 7.25. These routes are generally similar to the 1972 and 1977 Midway designs in both location of the track and altitude assignments. Some route straightening has been achieved in the northern arrival and departure routes.

7.1.6.2 The Post-1982 Task Force Concept at Chicago

The Chicago terminal area design appears to be quite well suited to the 1982 Task Force design concept. The application of the Task Force model, with some slight adaptation to account for the complex runway structure at O'Hare and the Midway satellite traffic, achieves a well organized traffic flow pattern with few severe altitude restrictions for either arrivals or departures.

The effect upon the design due to the incorporation of holding areas or $\pm$ 2 nm route widths rather than $\pm$ 1.5 nm route widths would appear to be minimal at Chicago. Sufficient airspace exists at each of the four low altitude arrival waypoints to develop holding pattern airspace.

7.1.7 <u>New York</u>

7.1.7.1 The Post-1982 New York Terminal Area Design

The post-1982 terminal area design deletes all of the conventional arrival and departure routes within the terminal area. Flows are no longer constrained by the placement of navigation aids and as a consequence the full use of parallel routes is made. The post-1982 designs are shown in Figures 7.26 and 7.27. The 6 nm route spacing restrictions that were applied to the 1977 design were continued in the post-1982 design in order to provide for a parallel offset route and the parent route. The traffic flow can be identified with alternating arrival and departure areas. However, they are not aligned with the octant concept described by the Task Force [1]. Traffic going to terminals adjacent to New York does go cross-grain to the general traffic flow in some cases but this traffic is all low altitude traffic and does not need to adhere to octant flow patterns beyond the low altitude departure or arrival waypoints. Traffic between New York and Philadelphia is shown in Figures 7.28 and 7.29 to illustrate this point.

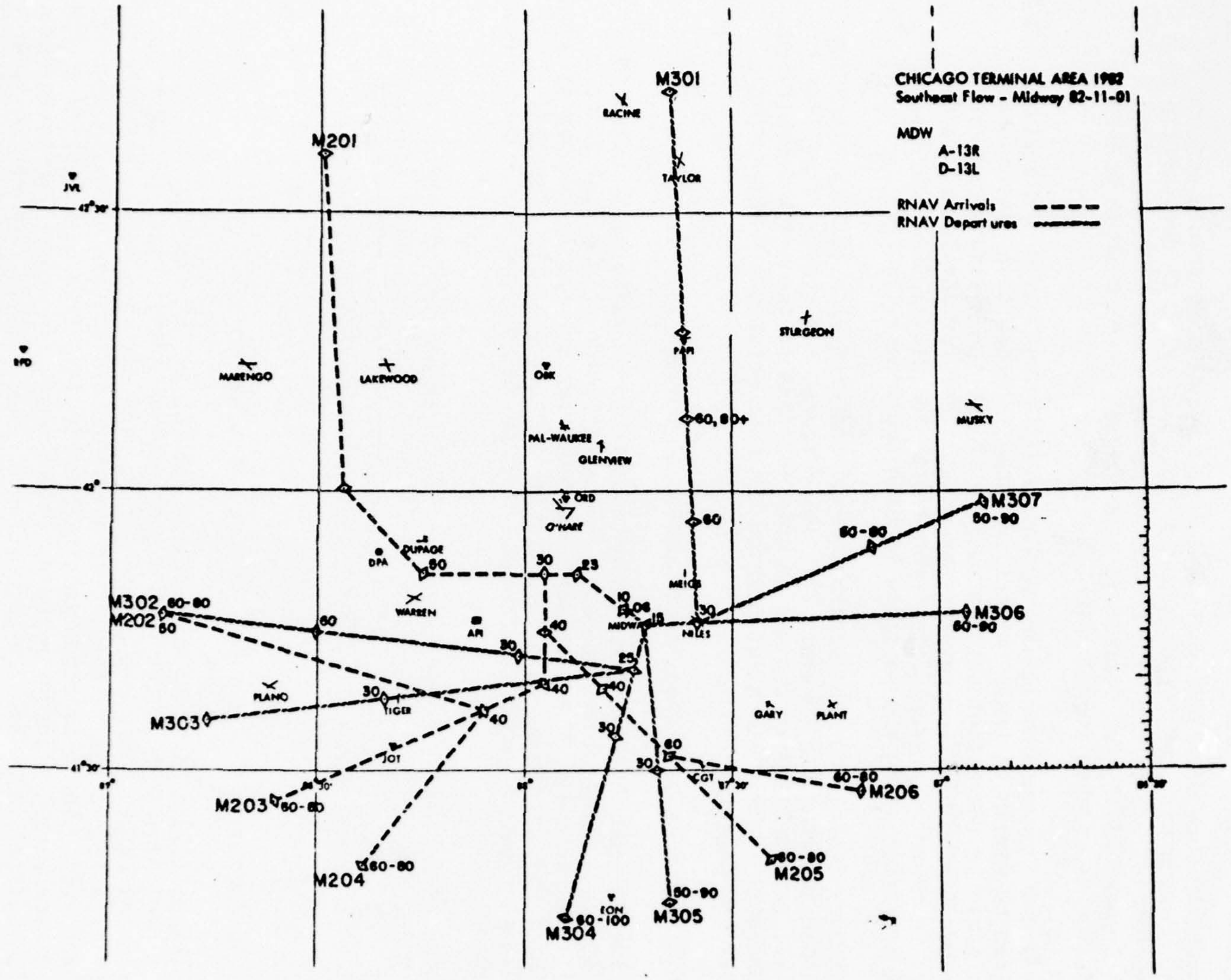


Figure 7.24 Chicago Terminal Area - Post-1982 RNAV Routes, Midway, Southeast Flow

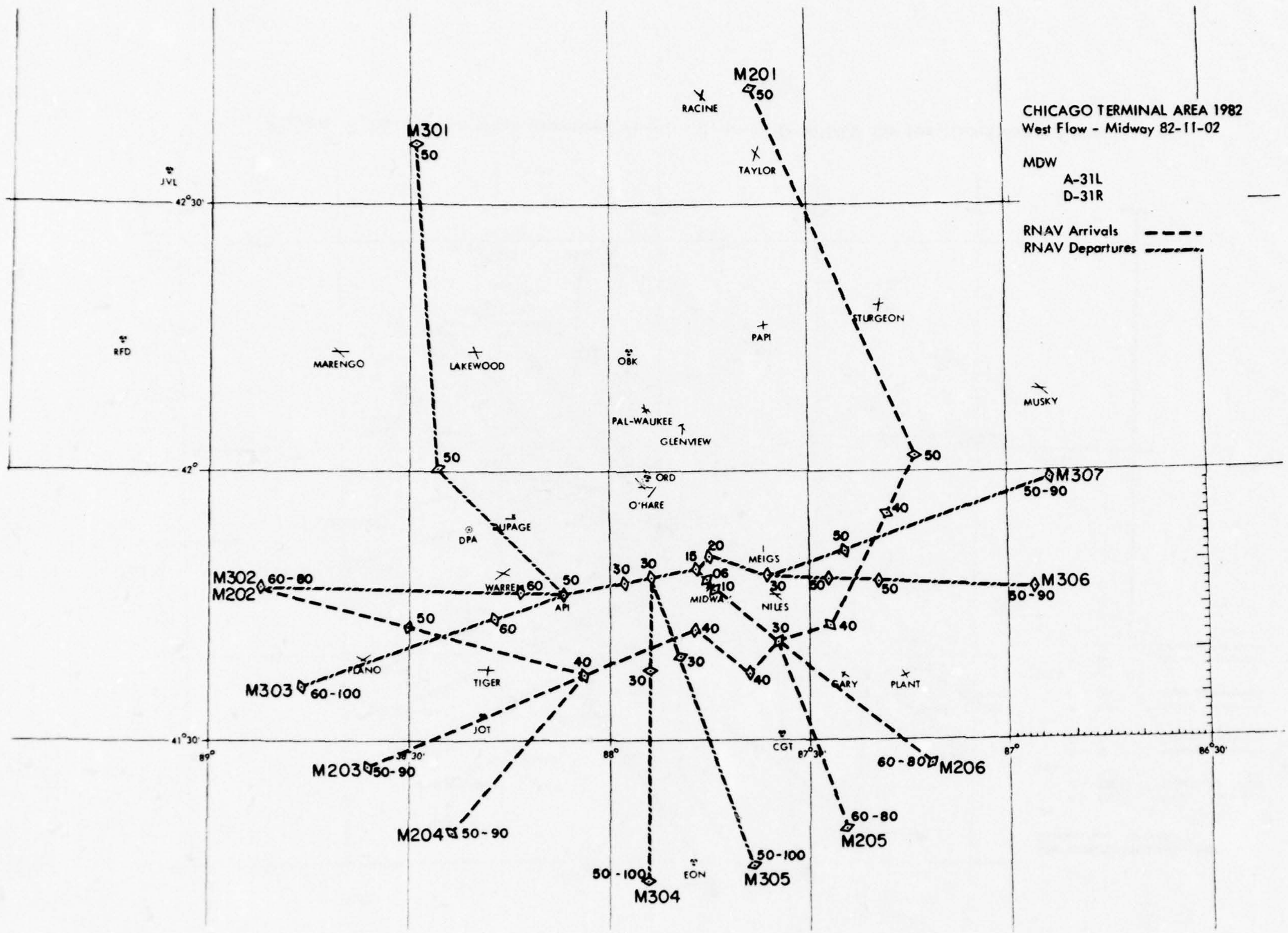


Figure 7.25 Chicago Terminal Area-Post-1982 RNAV Routes, Midway, West Flow

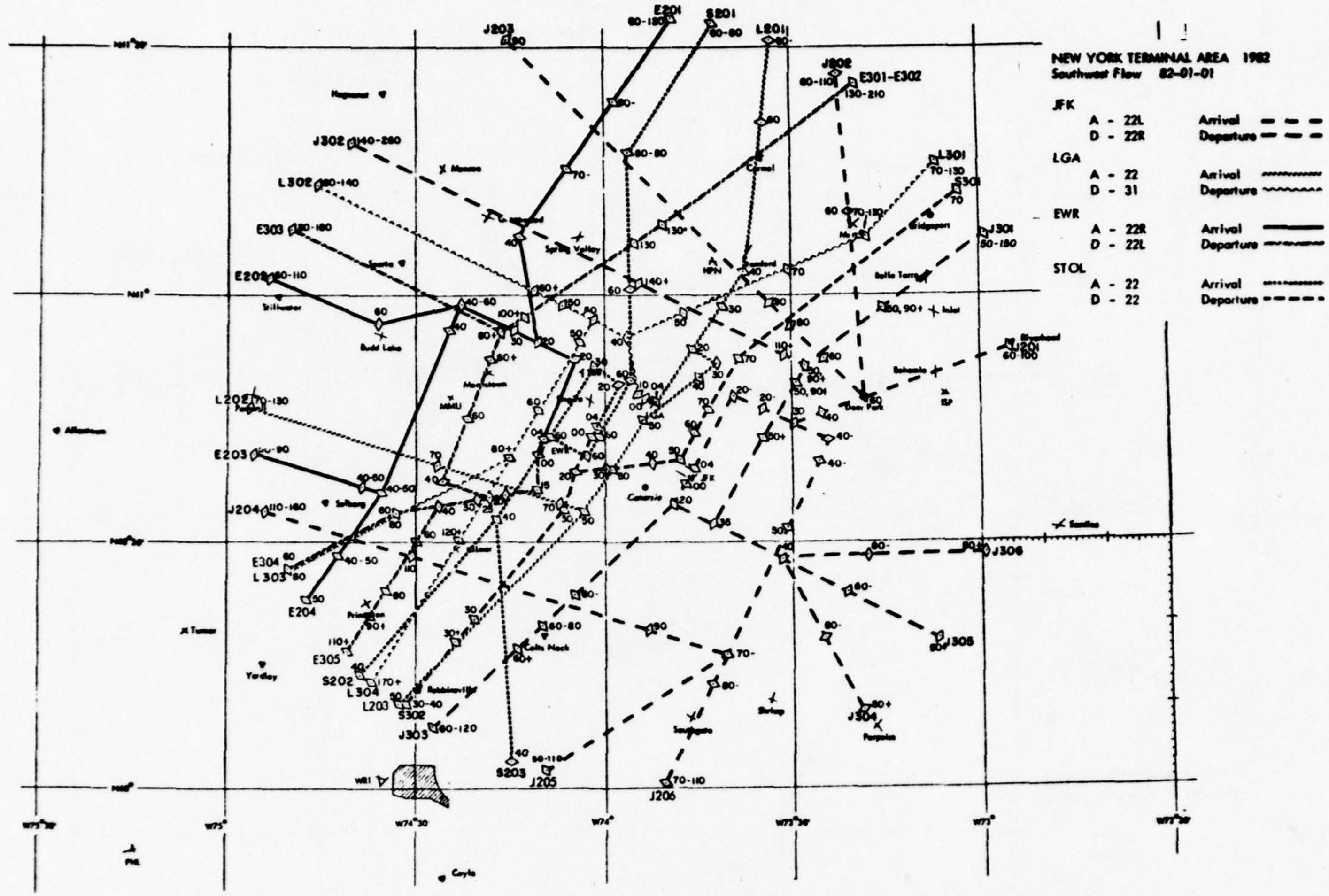


Figure 7.26 New York Terminal Area - Post-1982 RNAV Routes, Southwest Flow

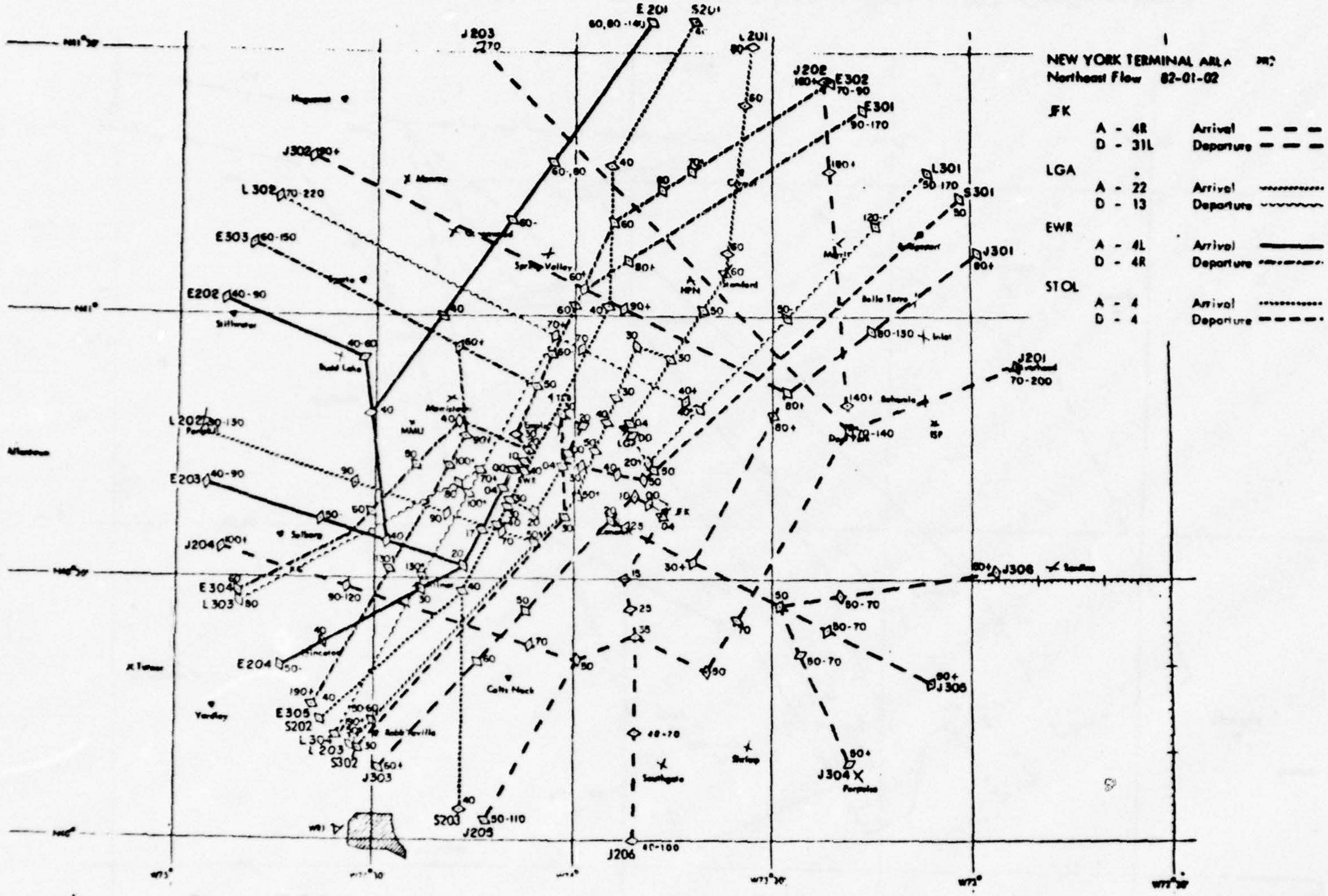


Figure 7.27 New York Terminal Area - Post-1982 RNAV Routes, Northeast Flow

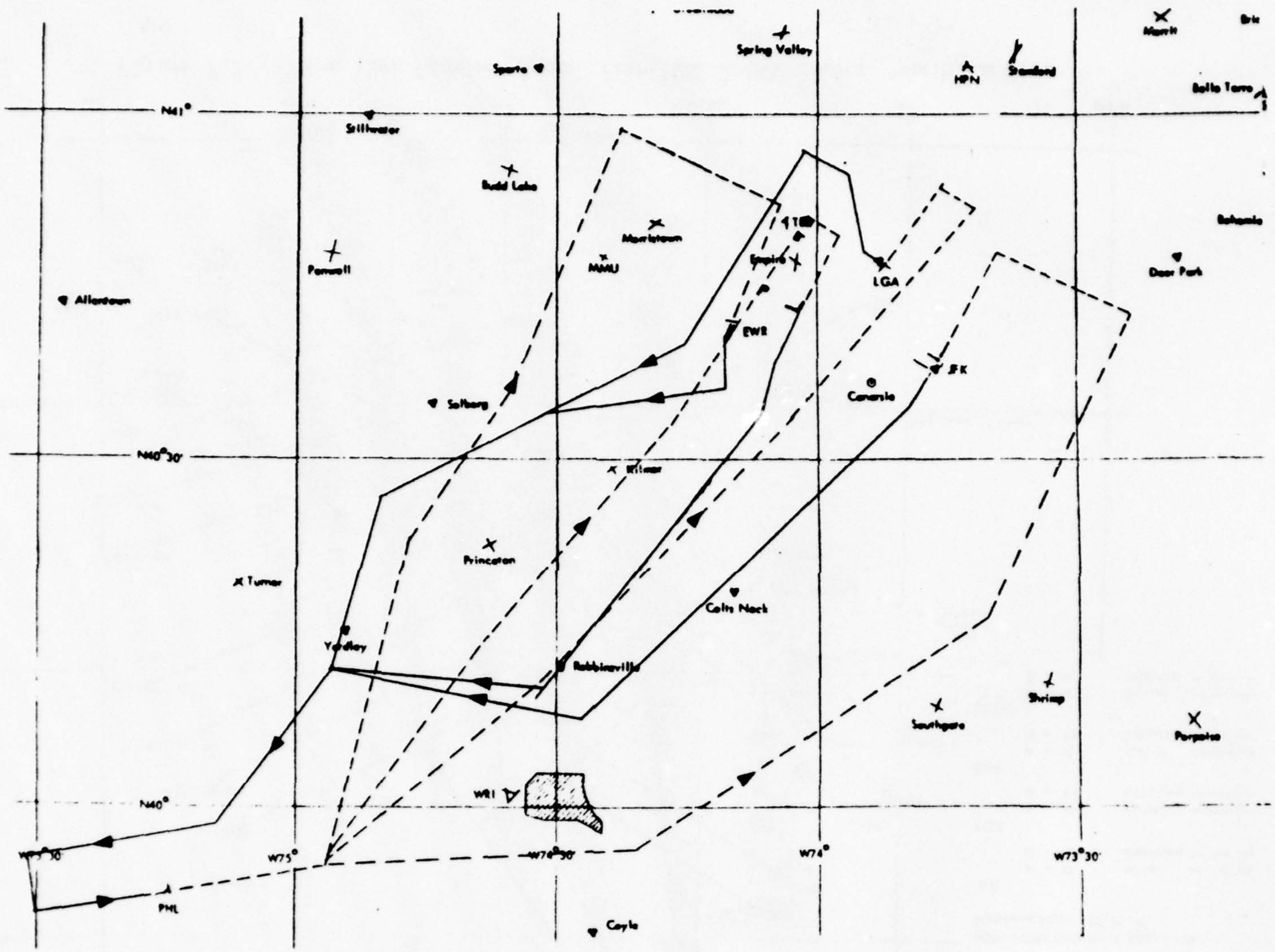


Figure 7.28 New York - Philadelphia Interface 1982, Configuration 1

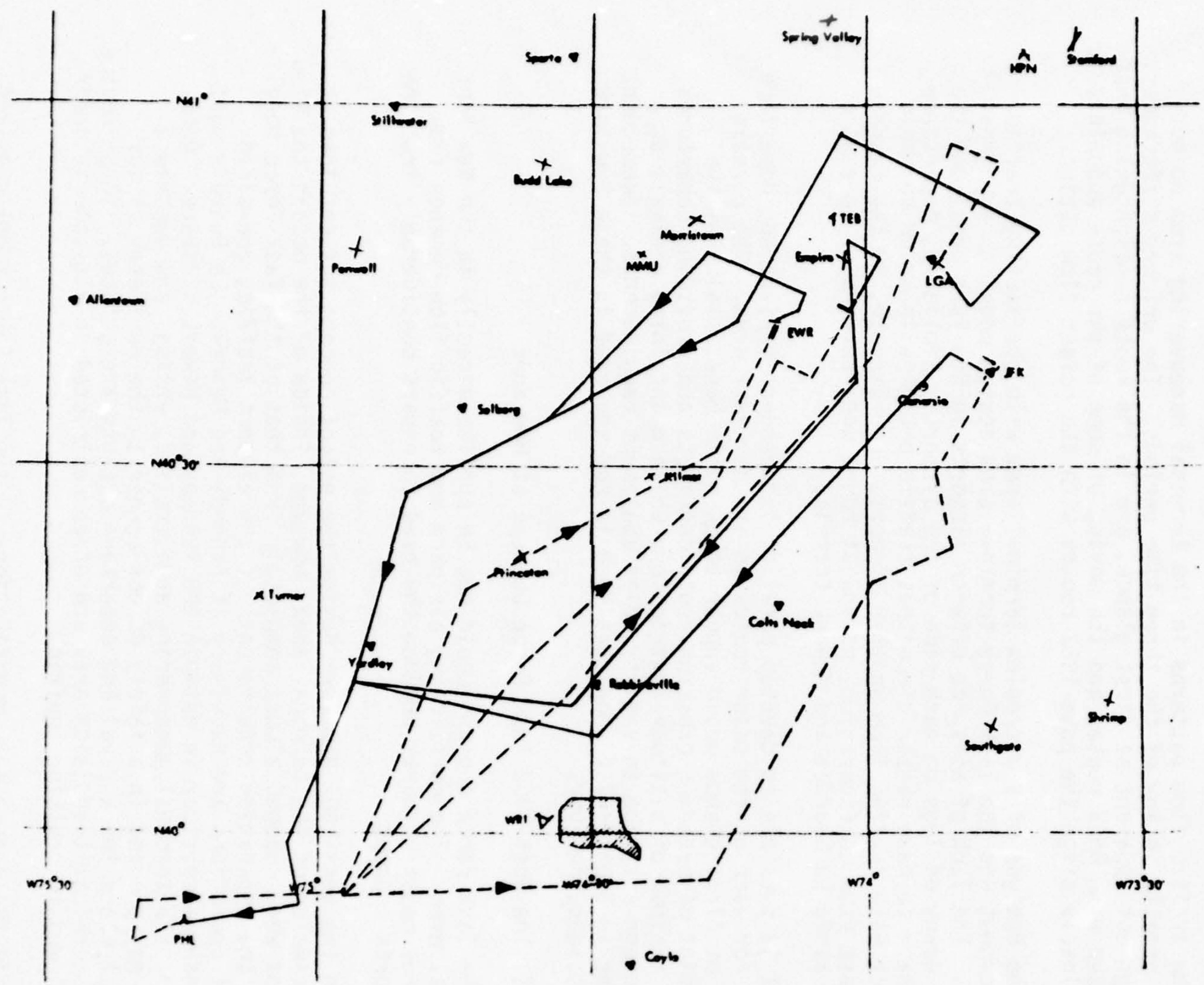


Figure 7.29 New York - Philadelphia Interface 1982, Configuration 2

The problem of providing interference-free routes in the transition region where low altitude traffic may be merging into one-way routes which was encountered in the 1977-1982 design is again seen in the post-1982 design. Consequently, low altitude traffic exited the terminal area at arrival waypoints separated from departure waypoints at the terminal boundary.

The traffic flow patterns in the terminal maneuvering area do not differ greatly in any of the three time periods. The primary differences, although not apparent at first glance, are in the route straightening that can occur with RNAV routes and the moving of some of the route endpoints to more closely align the post-1982 routes with the octant flow design.

The designs of a metroplex terminal area with conflicting traffic flows cannot use the Task Force terminal area design model to any great extent. The lack of airspace between airports in New York precludes the use of downwind legs on each side of the airport. Similarly, departures often have to make rather circuitous traffic patterns in order to avoid conflict with traffic from another airport. For example, in the Kennedy northeast flow configuration, northwest bound departures must go east of JFK to avoid La Guardia and Newark traffic.

It is possible to develop parallel independent arrival and departure routes for each of the major routes in the New York area. The parallel routes at first glance would appear to be quite beneficial from the standpoint of avoiding crossing route conflicts and providing departures with a minimum of altitude restrictions while maintaining arrivals at a high enough altitude to satisfy noise abatement requirements. Subsequent analyses in Section 7.2 show that such is not the case in these New York area designs, however.

7.1.7.2 The Post-1982 Task Force Concept at New York

The Task Force concept could not be applied directly in the New York terminal area. The conflicting airspace and traffic flow demands from the three major airports produce the need to depart considerably from the Task Force concept.

In the post-1982 New York design the octant concept was retained at the perimeter of the terminal area, however, inside of the octant the flow patterns were changed almost completely from that of the Task Force model. Due to the separation requirements of the airport traffic, one-sided airport operations are necessary at Kennedy and Newark. La Guardia must use a narrow corridor in between the Kennedy and Newark airspace. Once clear of the terminal maneuvering area traffic, arrival and departure routes may proceed in a fairly direct manner to the perimeter of the terminal where the arrival and departure octants are defined. These routes in the terminal transition area are often restricted in altitude in order to accommodate crossing traffic.

With these necessary modifications to the Task Force model required to achieve a terminal design at New York, the concept of standardized flows and waypoint locations appears to be unworkable at New York. The use of ± 2 nm route widths at New York could affect the post-1982 New York design.

Sufficient airspace is available with $\pm$ 2 nm routes to accommodate the basic route structure, however, there may not be enough airspace to accommodate parallel offset routes in some areas if the $\pm$ 2 nm route widths are used.

It was also found that the Task Force method of determining the extent of the terminal area could not be satisfactorily applied at New York. The Task Force recommended the encirclement of each major airport by a 45 nm circle and then drawing one large circle around the smaller 45 nm circles so that all the terminal circles were completely enclosed. If this were done at New York, then part of the Philadelphia airspace would be included in the New York area. Consequently, either the New York area would have to made smaller or the Philadelphia area would have to be included in the New York terminal area. To do the latter would have caused a chain reaction that would have necessitated including the entire east coast in one terminal area. Consequently, the alternative of reducing the New York area to more manageable dimensions was selected for implementation. What was ultimately done was to enclose the currently used New York feeder fix locations within the New York terminal area. The result was a 47 nm circle centered at a point 2 nm northwest of La Guardia. This method of determining the extent of the terminal area was satisfactory in New York and should be considered for use at other metroplex areas where similar problems can occur.

7.2 POST-1982 DESIGN ANALYSIS

7.2.1 Application of the Task Force Model

From a strictly mechanical point of view, the strict application of the Task Force terminal area model produced satisfactory designs in five of the seven terminal areas. That is, a route structure based on Task Force principles produced a route structure that could be used by ATC and the users which would permit the aircraft to enter or exit the terminal area. These terminals may be categorized as either single airport terminals or multiple airport terminals which have compatible traffic flows and runway orientations. These five terminals are:

Single Airport Terminals	Multiple Airport Terminals
New Orleans	Miami
Philadelphia	Chicago
Denver	

At the other two terminals the strict use of the Task Force model did not produce a satisfactory terminal design. The airspace demand of the multiple airports created conflicts in the traffic flow of the two airports. In addition, strict adherence to the octant flow concept sometimes forced routes into areas that were already crowded. Consequently, in these metroplex areas the Task Force model was altered to produce a satisfactory terminal design. The two terminals affected were New York and San Francisco. This problem with the Task Force model was ultimately resolved by the development of a modified terminal area design concept which is discussed in Section 8.

7.2.2 Design Validation

The validation of the post-1982 terminal design concept had two major aspects. The first was the creation of the designs themselves, thus demonstrating that a 1982 RNAV route structure can be developed for each of the seven terminal areas. The second aspect of the validation is directed to the question of the impact upon the user. Hopefully the user of the airspace should get some benefit from operating RNAV equipped aircraft. The analysis that was performed quantifies the amount of time and fuel savings or penalty that could be expected by typical turbojet aircraft operating in an RNAV terminal area environment.

7.2.2.1 ATC System Impact

As developed from the Task Force model, the implementation of the post-1982 terminal area design would cause no negative impact upon the controller workload. Although a real time simulation of this initial New York 1982 terminal design was not undertaken, the 1977-1982 and initial post-1982 route structures are similar enough to indicate that similar results of substantial controller workload reduction would be forthcoming from an analysis and simulation of the post-1982 route structure. In addition the results of the 1972-1977 and 1977-1982 simulations and the modified post-1982 simulation, discussed in Section 7.4.3.4, are sufficiently consistent to indicate that the specific route design had little impact upon the results. The major impact was due to the RNAV traffic control procedures. The controller did not have to issue nearly as many flight path control instructions in high percentage RNAV operations as he did in low percentage RNAV operations. Consequently, the major impact of the post-1982 terminal designs upon the ATC system would appear to be in the area of increased controller productivity and reduced controller workload. This subject is covered in detail in References 13, 14 and 18.

7.2.2.2 Route Length and Altitude Restriction Analysis of Initial Designs

Some measure of the quality of the terminal area design produced during this investigation was necessary in order to determine if the RNAV designs produced a benefit for the user. The technique used for evaluating this benefit was to quantify the time and fuel improvements of several aircraft operating over the RNAV designed route structure for post-1982 as compared to the current 1972-1977 route structure. The performance characteristics of four air carrier turbojet aircraft were selected for the analysis. These aircraft are:

McDonnell Douglas DC-9
Boeing 727
McDonnell Douglas DC-8
Boeing 747

Standard handbook climb and descent data [6,7,11,12] for these aircraft were used to compute the amount of time and fuel used on each design route. The aircraft were permitted to climb or descend at their handbook values unless an altitude restriction was encountered. When restrictions were

encountered, the aircraft was assumed to fly level until a point was reached such that the restriction was changed. Examples of these restrictions are shown in Figure 7.30. It can be seen that Aircraft A reaches an altitude restriction which interrupts his optimum handbook climb. Aircraft B on the other hand is a poorer performing aircraft and B does not encounter the restriction. A similar situation exists in the case of the descent. Aircraft D has his descent interrupted by an altitude restriction while Aircraft C can descent without restriction due to the shallower profile for Aircraft C.

Traffic was approtioned to each route in the terminal area by using data on city pair traffic from the 1971 peak day IFR records [9]. Traffic was assumed to use the departure or arrival route that was most closely aligned with the origin or destination city. Benefits were then computed by comparing the RNAV terminal design time and fuel consumption with the VOR terminal design time and fuel consumption.

The initial terminal area route structures which were based on a strict application of the Task Force guidelines for nine of the thirteen airports (seven terminal areas) were considered in this analysis. The basis for comparison was the initial 1972 RNAV route structures which were developed from current VOR/radar vector routes. The primary airport in each of the seven terminal areas was analyzed, except for New York where all three airports were considered. The results of the analysis presented a rather mixed benefit/penalty picture. Three of the airports had a significant benefit associated with the use of the Task Force design concept. These airports are shown in Table 7.1.

TABLE 7.1 Airports Which Exhibited a Definite User Benefit in Using a Strict Application of the Task Force Terminal Design Concept

Airport	Flow Orientation	DC-9		B727		DC-8		B747	
		Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)
Philadelphia	East	63	0.60	89	0.65	152	0.62	250	0.73
	West	124	1.21	177	1.30	317	1.34	483	1.44
Miami	East	65	0.70	87	0.73	140	0.70	168	0.71
	West	102	1.08	138	1.11	212	1.01	303	1.06
Chicago O'Hare	Southeast	25	0.23	36	0.26	75	0.29	106	0.31
	West	32	0.34	45	0.35	74	0.36	92	0.35

/Note/ The positive values in this table indicate a benefit to the airspace user.

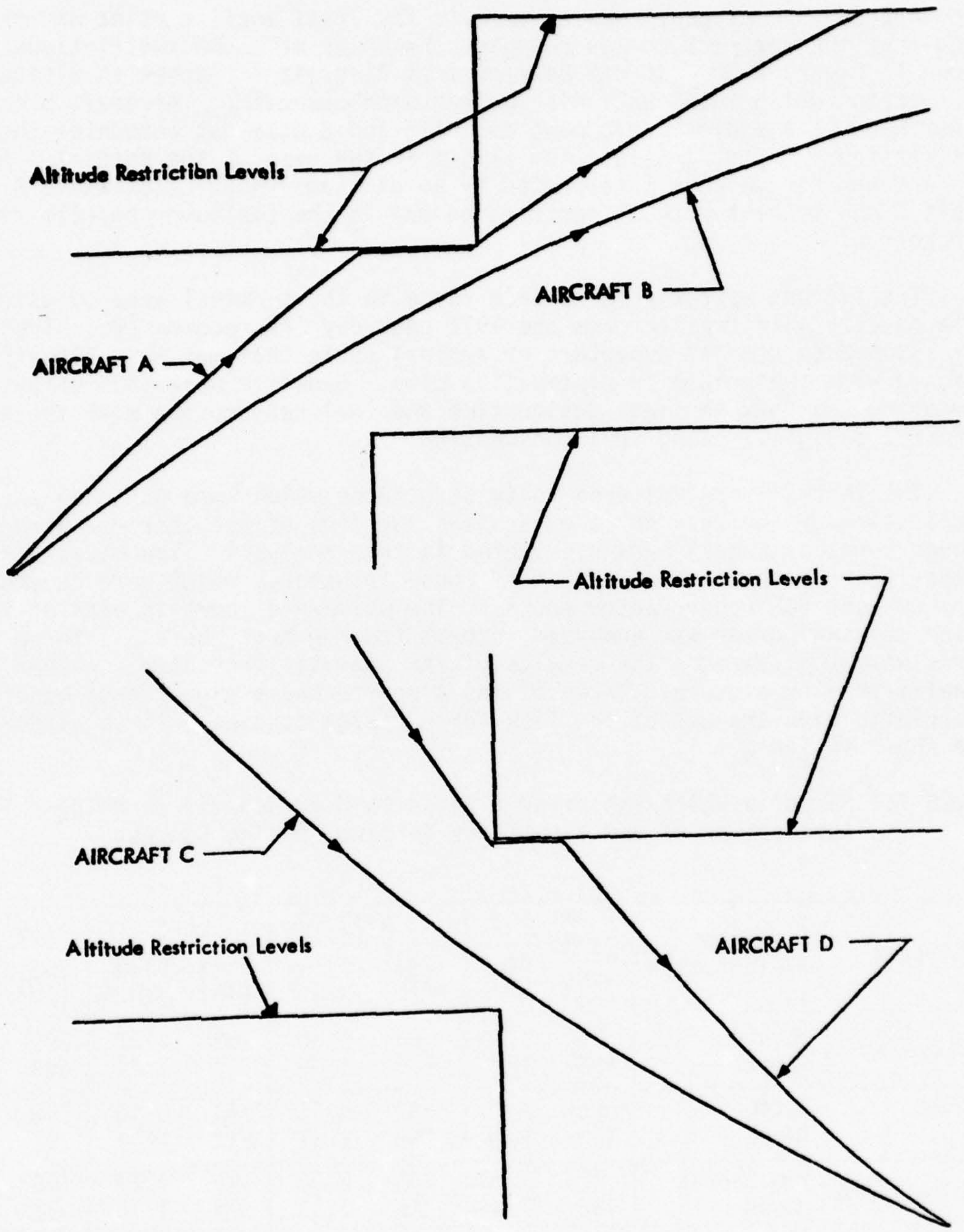


Figure 7.30 Altitude Restrictions During Climb and Descent

These terminal areas fall into the category of those having a moderately complex terminal area traffic pattern but yet still having a flow pattern which is quite compatible with the Task Force design concept.

A second group of three airports showed rather mixed benefit/penalty results. These airports showed a benefit to one of the terminal flow configurations but a similar sized penalty on the other runway configuration. These airports are listed in Table 7.2.

TABLE 7.2 Airports Which Exhibited a Mixed User Benefit/Penalty Characteristic in Using a Strict Application of the Task Force Terminal Design Concept

Airport	Flow Orientation	DC-9		B727		DC-8		B747	
		Fuel (Lb)	Time (Min)	Fuel (Lb)	Time (Min)	Fuel (Lb)	Time (Min)	Fuel (Lb)	Time (Min)
Denver	West	-34	-0.32	-43	-0.31	-57	-0.30	-66	-0.31
	East	44	0.44	66	0.46	114	0.47	173	0.43
New Orleans	East	-20	-0.19	-26	-0.16	-18	-0.16	-26	-0.12
	North	17	0.19	25	0.19	50	0.18	102	0.21
San Francisco	West	-23	-0.26	-28	-0.31	-88	-0.33	-145	-0.36
	Southeast	54	0.56	80	0.56	117	0.57	188	0.57

Note: The positive values in this table indicate a benefit to the airspace user; minus signs indicate those areas where the net effect was negative.

These airports fall into either one of two categories. First, Denver and New Orleans are relatively simple single airport terminals with a straightforward traffic flow in both the 1972 VOR and the post-1982 RNAV route structures. Consequently, little benefit or penalty is associated with either terminal design.

San Francisco is a complex terminal in which the Task Force model could not be directly applied. The resultant San Francisco RNAV route design contains many altitude restriction areas as does the 1972 VOR route design. From the results of the route length and altitude restriction analysis program these restrictions have about the same effect in both time periods. Consequently, the time and fuel penalties associated with these restrictions cancel each other out. Consequently, the overall impact of the RNAV routes in the post-1982 San Francisco design would be no more economical for the user than the 1972 VOR routes that are in current use.

A third group comprised of the three New York area airports showed a rather negative result. In these designs either one or both of the RNAV route structures showed a considerable penalty in both time and fuel for the post-1982 RNAV route structure. The New York results are presented in Table 7.3. The negative results of New York and the mixed results at Denver, New Orleans and San Francisco strongly suggested that some reconsideration of the Task Force design concept as it was applied to the terminal area was definitely necessary. This reconsideration and the resultant designs are presented in Section 7.4.

Table 7.3 Airports Which Exhibited a Definite User Penalty in Using the Post-1982 Terminal Area Routes Based Upon a Strict Application of the RNAV Task Force Terminal Design Concept

Airport	Flow Orientation	DC-9		B727		DC-8		B747	
		Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)
New York-JFK	Southwest	-197	-1.14	-277	-1.01	-433	-1.09	-594	-1.10
	Northeast	68	0.64	82	0.63	151	0.60	267	0.56
New York-LGA	Southwest	2	0.03	16	-0.05	-50	0.00	-152	-0.11
	Northeast	-84	-1.33	-98	-1.53	-299	-1.31	-536	-1.50
Newark	Southwest	-141	-1.33	-199	-1.32	-294	-1.33	-468	-1.32
	Northeast	-21	-0.06	-25	-0.04	-51	-0.04	-3	-0.08

/Note/ The positive values in this table indicate a benefit to the airspace user; minus signs indicate those areas where the net effect was negative.

7.3 VNAV DESIGNS AND ANALYSIS

This section describes several of the problem areas which were encountered and design techniques which were developed in applying the Task Force fixed gradient VNAV terminal area design concept to the initial post-1982 New York and New Orleans RNAV terminal area designs. The use of the post-1982 RNAV design does not imply that fixed gradient VNAV routes could not be used in the 1972-1977 or the 1977-1982 designs. These RNAV designs could have been used as a basis for the fixed gradient VNAV design as well. The objective of the design task was to create a terminal area design using fixed gradient VNAV profiles eclusively within the terminal area. In order to provide a consistent set of terminal area designs for the New York and New Orleans areas, the post-1982 terminal area designs described in Section 7.1 were used as the bases for the VNAV terminal area design effort. The major difference between a fixed gradient VNAV design and the post-1982 RNAV New York design is that the fixed gradient VNAV design is constructed to a specified gradient or gradients while the RNAV design is based upon unrestricted climbs or descents between level flight segments.

Guidelines

The guidelines which were established for this initial phase of the VNAV design task were threefold:

1. Utilize the post-1982 Task Force design guidelines as a starting point for the plan view of the fixed gradient VNAV design.

2. Provide routes at optimum vertical gradients everywhere possible.

3. Provide routes at shallower than optimum gradients and routes that terminate at lower cruise altitudes than the optimum routes.

These guidelines were established in order that the fixed gradient VNAV design be predicated on the Task Force post-1982 design concepts to the maximum extent possible and that all users of the terminal area, both high and low performance aircraft and long haul and short haul traffic, be considered in the design.

Problems Areas

The use of VNAV avionics in the terminal area brings to light several problem areas that were not encountered in conventional VOR and RNAV terminal area designs. These problems include:

1. Specification of VNAV profile type

2. Selection of vertical gradients

3. Separation of VNAV routes, particularly in the vertical direction

4. Accommodation of multiple enroute altitudes

5. Consideration of horizontal and vertical offset paths

Two types of VNAV profiles were considered as potential candidates for the VNAV routes, as described in Section 3.5. The specified altitude profile (SAP) type of design was selected as the design model because of its equipment compatibility characteristic and its ability to accommodate the lower performance aircraft.

As described in Section 3.5.1, the following maximum gradients were adapted.

Climb	=	400 ft/nm up to 10,000 gt
		300 ft/nm between 10,000 ft and 18,000 ft
		200 ft/nm above 18,000 ft
Descent	=	300 ft/nm at all altitudes

Route separation criteria for fixed gradient VNAV routes have not yet been established. Consequently, based upon the lateral and vertical equipment accuracy figures for post-1982 in the FAA/Industry RNAV Task Force Report [1] and the separation equations of Appendix A, the following minimum separation equation for vertical routes was utilized:

$$S = \frac{L_1}{\sin\theta}\left|\tan\beta_1 \cos\theta - \tan\beta_2\right| + \frac{L_2}{\sin\theta}\left|\tan\beta_1 - \tan\beta_2 \cos\theta\right| + V_1 + V_2 + B$$

Where S = minimum vertical separation of fixed gradient VNAV routes at the intersection of their centerlines

$L_{1,2}$ = lateral semi tube protected airspace for route 1 or 2

$V_{1,2}$ = vertical semi tube protected airspace for route 1 or 2

$\beta_{1,2}$ = climb gradient for route 1 or 2 (always positive)

B = airspace buffer area between the routes

θ = angle of intersection between the two VNAV routes

Some typical curves of separation vs intersection angle are shown in Figure 7.31. These separation curves were plotted at a point that is 25 miles from a VORTAC at the tangent point of the route. These separation values are discussed more thoroughly in Appendix A.

Design Approach

The terminal designs using fixed gradient VNAV profiles were developed by using a combination of the plan view and profile view of each route. The design process is outlined below.

1. Develop plan and profile views for each route in the terminal area. The plan view was taken from the post-1982 terminal design which was based on the Task Force terminal concept. The profile views were developed according to the gradients discussed earlier in this section.

2. Identify all route crossings on the plan view and display on the profile view at the appropriate flight path distance and altitude. Resolve conflict situations by lowering VNAV profiles or moving routes on the plan view.

3. Develop VNAV routes on the profile view for altitudes below the specified gradients for each route and display the crossing altitudes on those affected profile views. Resolve conflict situations. (The resolution of conflicts is a rather time-consuming trial and error method of developing conflict free VNAV routes in the terminal area).

4. Create waypoints at route turn points and at other points which help expedite the flow of traffic. In order to minimize pilot work-load a minimum number of waypoints should be used wherever possible. Also, waypoints are spaced at least 10 nm apart unless it is necessary from a conflict resolution standpoint or a turning point standpoint to locate them closer than 10 nm apart.

5. Resolve all conflict situations using standard gradients or a less than standard gradient.

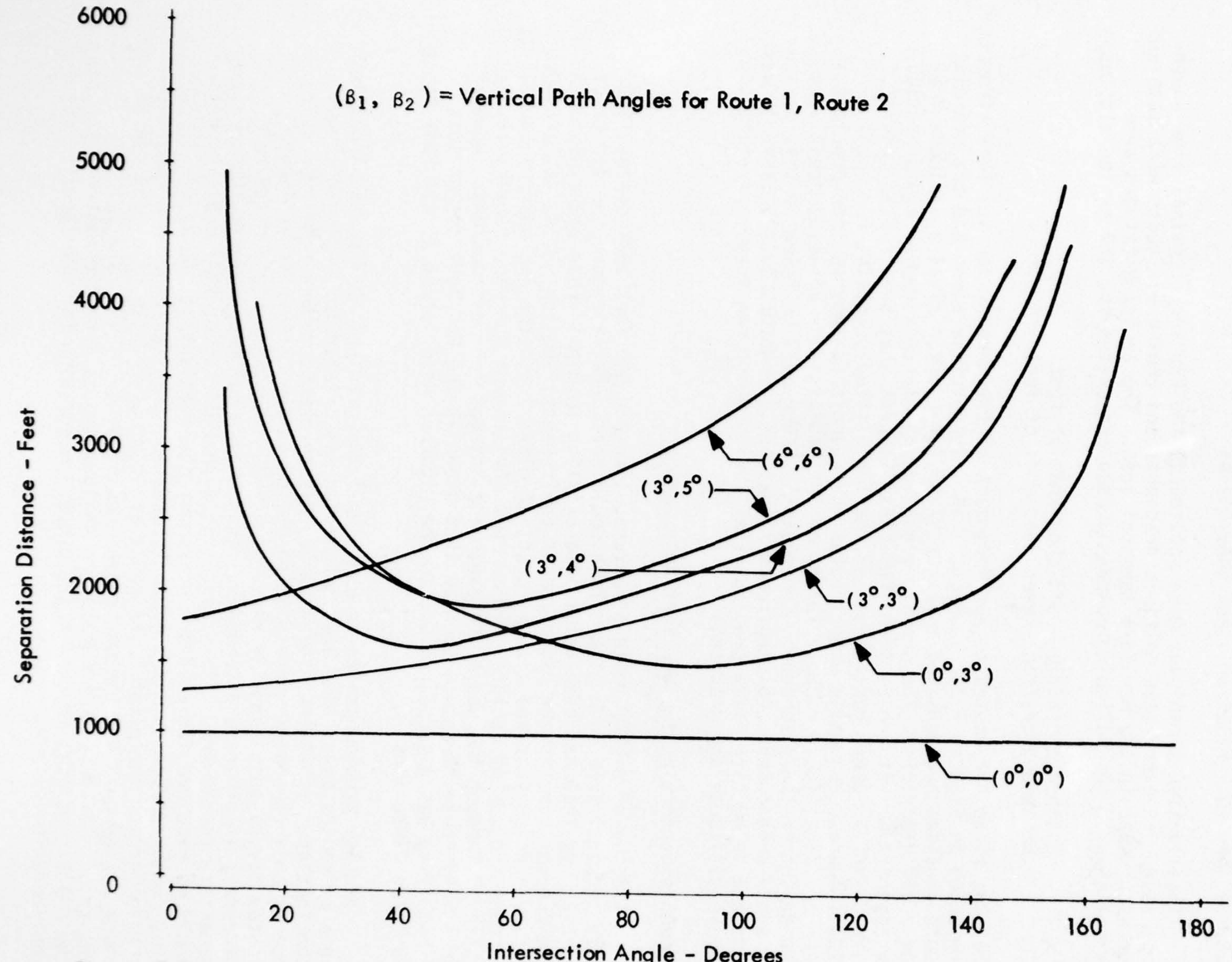


Figure 7.31 Minimum Fixed Gradient VNAV Route Separation Contours

7.3.1 POST-1982 FIXED GRADIENT VNAV DESIGNS

7.3.1.1 New York Fixed Gradient VNAV Design

These design techniques were applied to the New York terminal area southwest flow. In every case multiple gradients and cruise altitudes were obtained for each route in the New York terminal area. The cruise altitudes were established on the following currently used convention for IFR cruise altitudes.

Eastbound traffic - odd thousands of feet
Westbound traffic - even thousands of feet

The plan views for routes to and from each of the three major New York airports are shown in Figures 7.32, 7.33 and 7.34. The profile views and the crossing route problems are depicted in Figure 7.35 for a JFK arrival and Figure 7.36 for a JFK departure. The profile views for all three airports are presented in Appendix B. It can be seen from these figures that some routes intersect with numerous other routes such as the low altitude profiles for route J204 (Figure 7.35) while other routes have almost no intersection problems, such as J303 (Figure 7.36). The number of conflicts is affected greatly by the design of the plan view. Consequently, care must be taken in this design to avoid unnecessary crossing route situations. However, in all cases it was possible to develop fixed gradient VNAV routes which can serve a variety of cruise altitudes and gradients.

Comments Concerning the New York VNAV Design

The use of a VNAV route structure, like the New York VNAV design, in a busy terminal area such as New York would considerably reduce the degree of flexibility that has been built into existing terminal route structures. At the present time in the radar vector environment, the controller can provide for sequencing fast and slow aircraft of differing climb and descent capability through the use of vectors. In an RNAV environment the same flexibility is achieved through the use of "offset" and "direct to" instructions. However, in a VNAV route structure such as that shown in the New York design this flexibility has disappeared due to the rigorous description of the VNAV route in three dimensions.

Another problem arises in applying fixed-gradient VNAV route structures in a metroplex area. The New York design was created for a single runway combination. If Newark, for example, had to change runway flows for some operational reason, a corresponding change in the La Guardia and Kennedy routes beyond that normally required for 2D operations would often be necessary in order to accommodate the new airspace requirements that would be necessary for Newark. It is conceivable that different VNAV route structures would be required for each set of runway combinations at the major airports. This could produce an undesirable information transfer problem for both the controller and the pilot. The route assignments for the pilot and the airspace assignments for the controller could change as the runway in use changes. This problem would have a serious impact upon the controller's and the pilot's ability to obtain the proper information for the specific runway configuration in use.

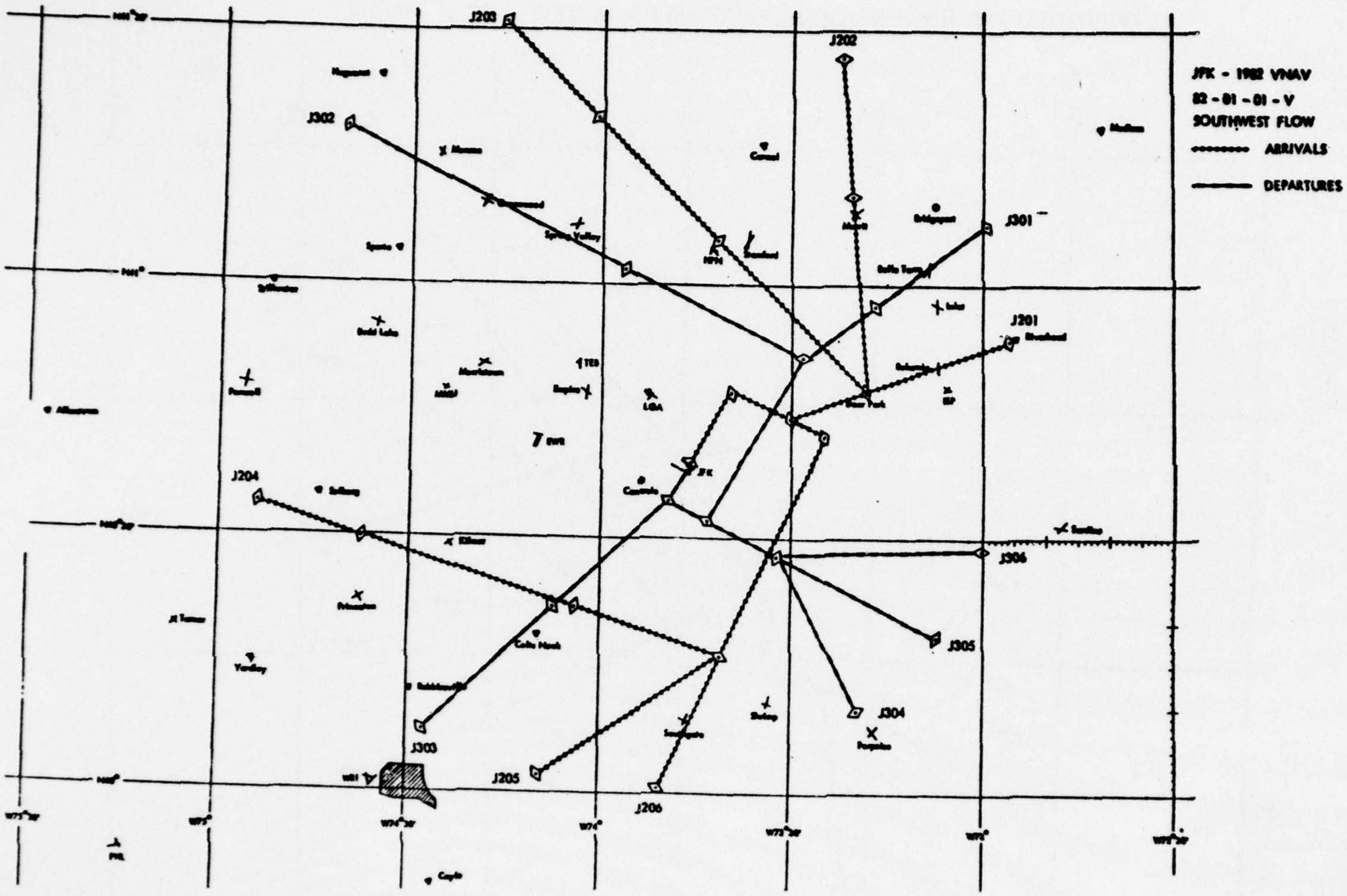


Figure 7.32 JFK Fixed Gradient VNAV Arrivals and Departures

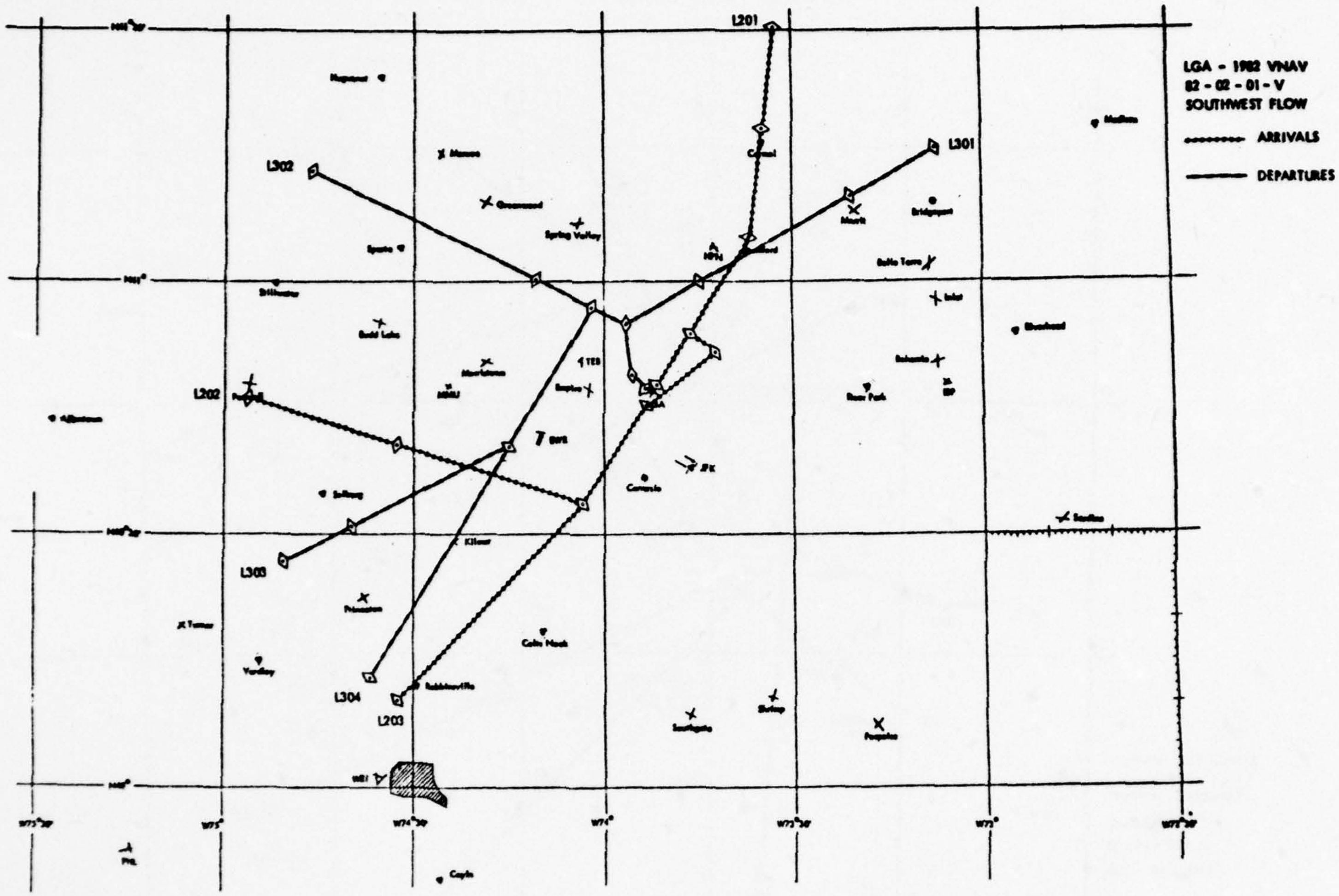


Figure 7.33 LGA Fixed Gradient VNAV Arrivals and Departures

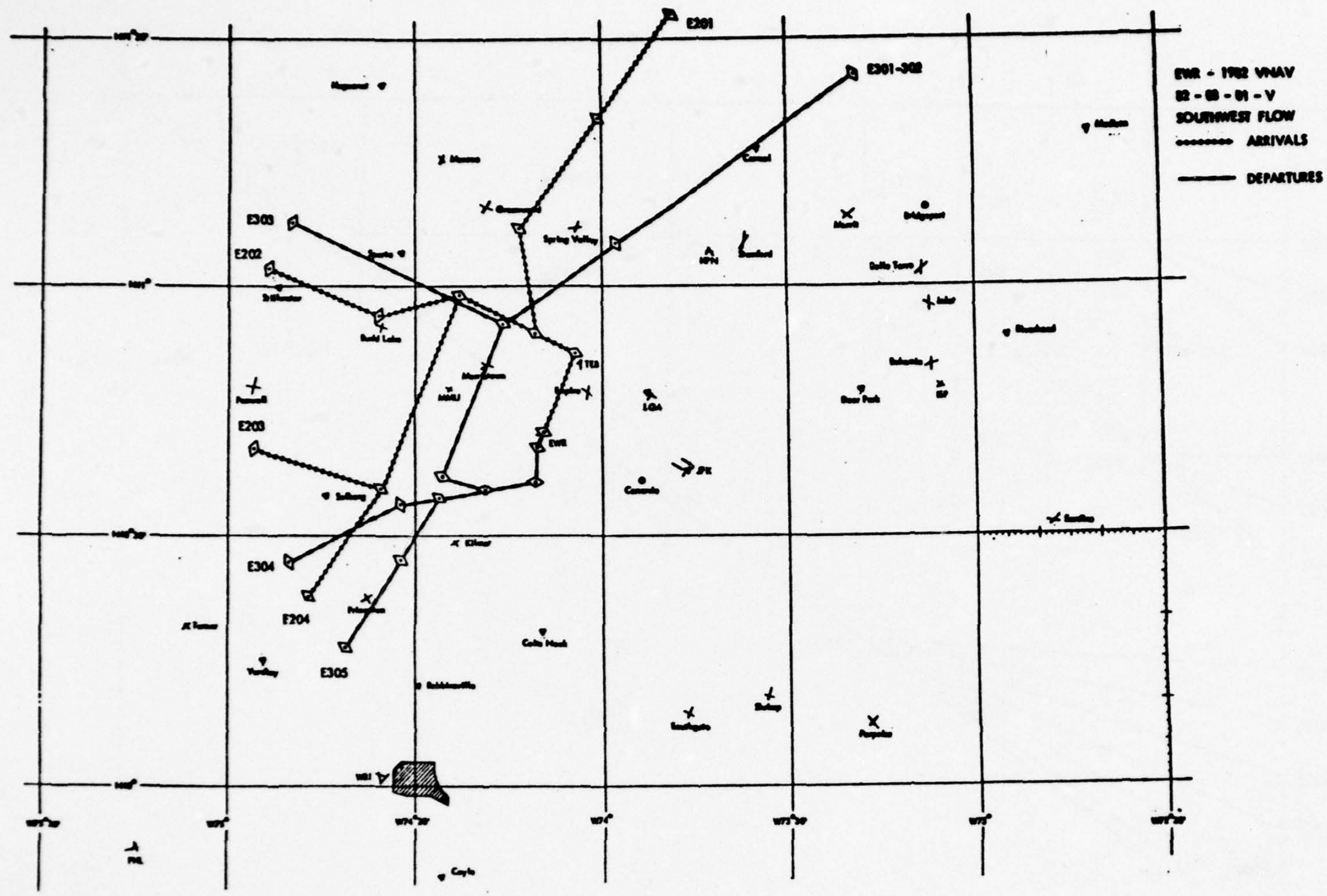


Figure 7.34 EWR Fixed Gradient VNAV Arrivals and Departures

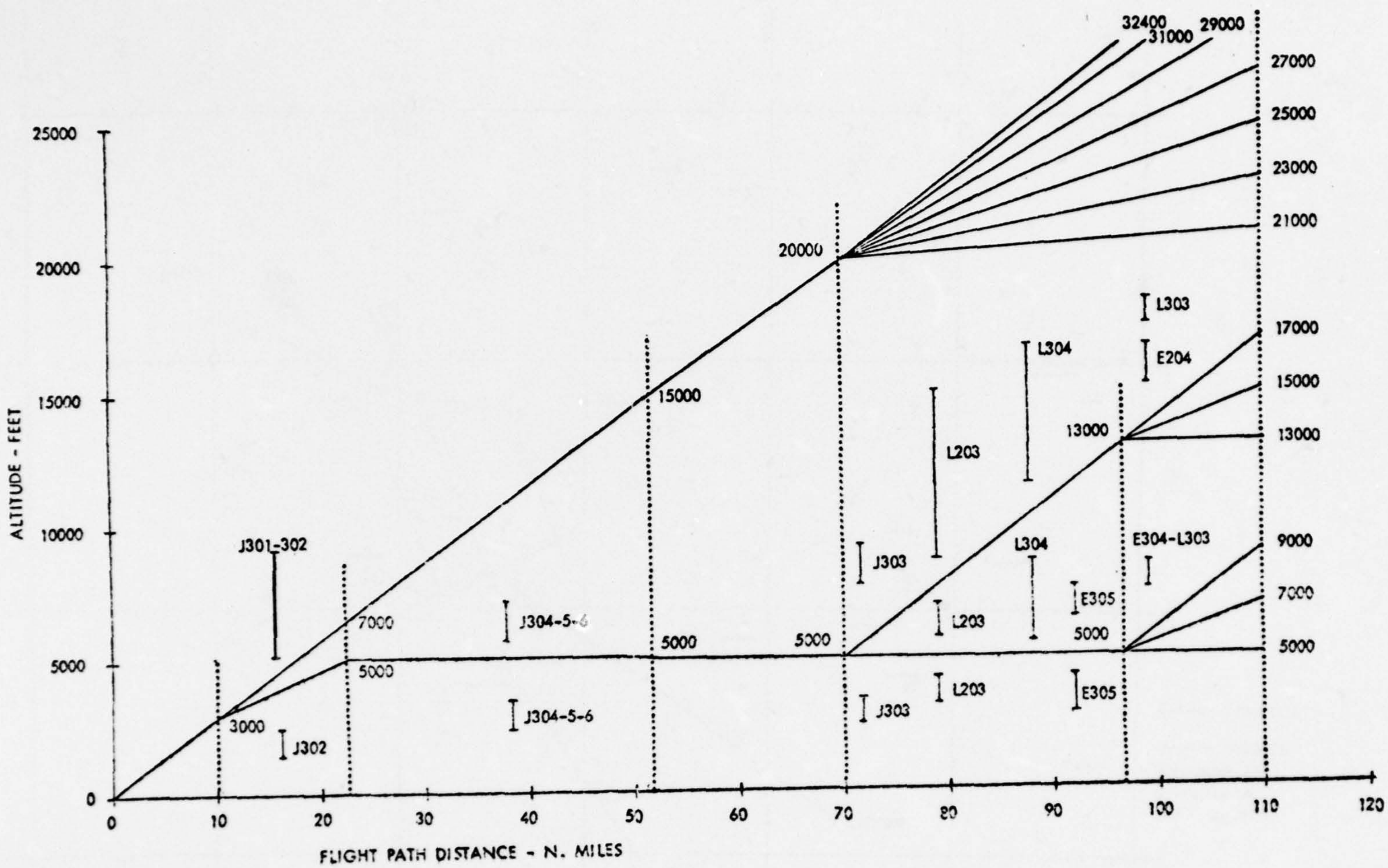


Figure 7.35 Route J204 (Arrival) Configuration 1

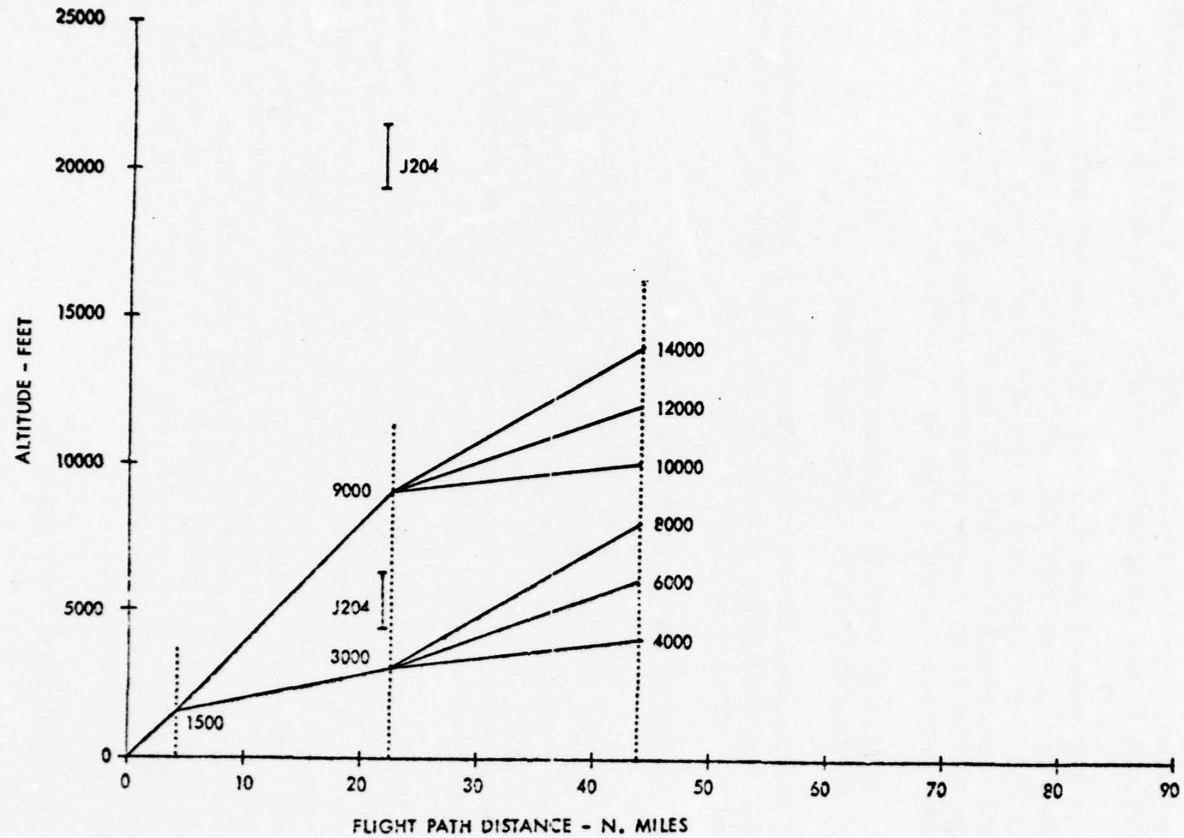


Figure 7.36 Route J303 (Departure) Configuration 1

7.3.1.2 New Orleans Fixed Gradient VNAV Design

The VNAV design technique was also applied to both traffic flows at New Orleans. It was desired to check the effectiveness of a VNAV design for a small to medium size terminal area as well as for a large area like New York. Since New Orleans was the smallest area of the seven terminals in terms of IFR operations it was selected for a VNAV route design task.

As in the case of New York the 1982 terminal design was used as a basis of the VNAV design and 100% VNAV was assumed. The same climb and descent gradients that were used in the New York design were used at New Orleans. The routes were plotted in both the plan view and the profile view out to the perimeter of the 45 nm circle around New Orleans. The perimeter altitudes were based upon the current airspace convention of:

Eastbound traffic - odd thousands of feet
Westbound traffic - even thousands of feet

The VNAV routes for New Orleans are presented in Appendix C. The plan view and a representative example of the profile view for the New Orleans east flow are shown in Figures 7.37 and 7.38.

Comments Concerning the New Orleans VNAV Design

The VNAV design at New Orleans creates a very structured, highly organized terminal route pattern. If an aircraft desires to exit the terminal on a specified route at a specific altitude, the three dimensional location of that aircraft is completely determined. This high degree of organization however, can lead to inefficient climb profiles and excessive airspeed restrictions for aircraft in-trail.

The New Orleans VNAV design demonstrated that it is technically possible to develop a fixed- gradient VNAV route structure for both traffic flows at New Orleans. There is sufficient airspace, both laterally and vertically, to provide separation assurance on all of the VNAV routes shown in Figure 7.37. The operational desirability of such a route structure from the ATC and the user's standpoint is not apparent in these route structures however. In fact, analysis of user benefits of fixed-gradient routes in Section 7.3.2 indicates that a user penalty rather than a benefit is usually associated with fixed-gradient climb and descent procedures. In addition analyses from Appendices A and E indicate that no ATC benefits can be attributed to fixed-gradient VNAV procedures.

7.3.2 Fixed Gradient VNAV Analysis

The climb performance characteristics of three different jet aircraft were analyzed in order to assess the impact of fixed gradient VNAV climb procedures on direct operating cost. These aircraft types span the primary range of jet aircraft used today in air transport operations. Table 7.4 summarizes the results of the VNAV climb fuel and time analysis. The numbers presented in this table represent the additional time or fuel consumption required for a VNAV climb as compared to a standard handbook climb. Several VNAV climb gradients are presented. The numbers in Table 7.4 represent climb procedures from sea level to 10,000 feet.

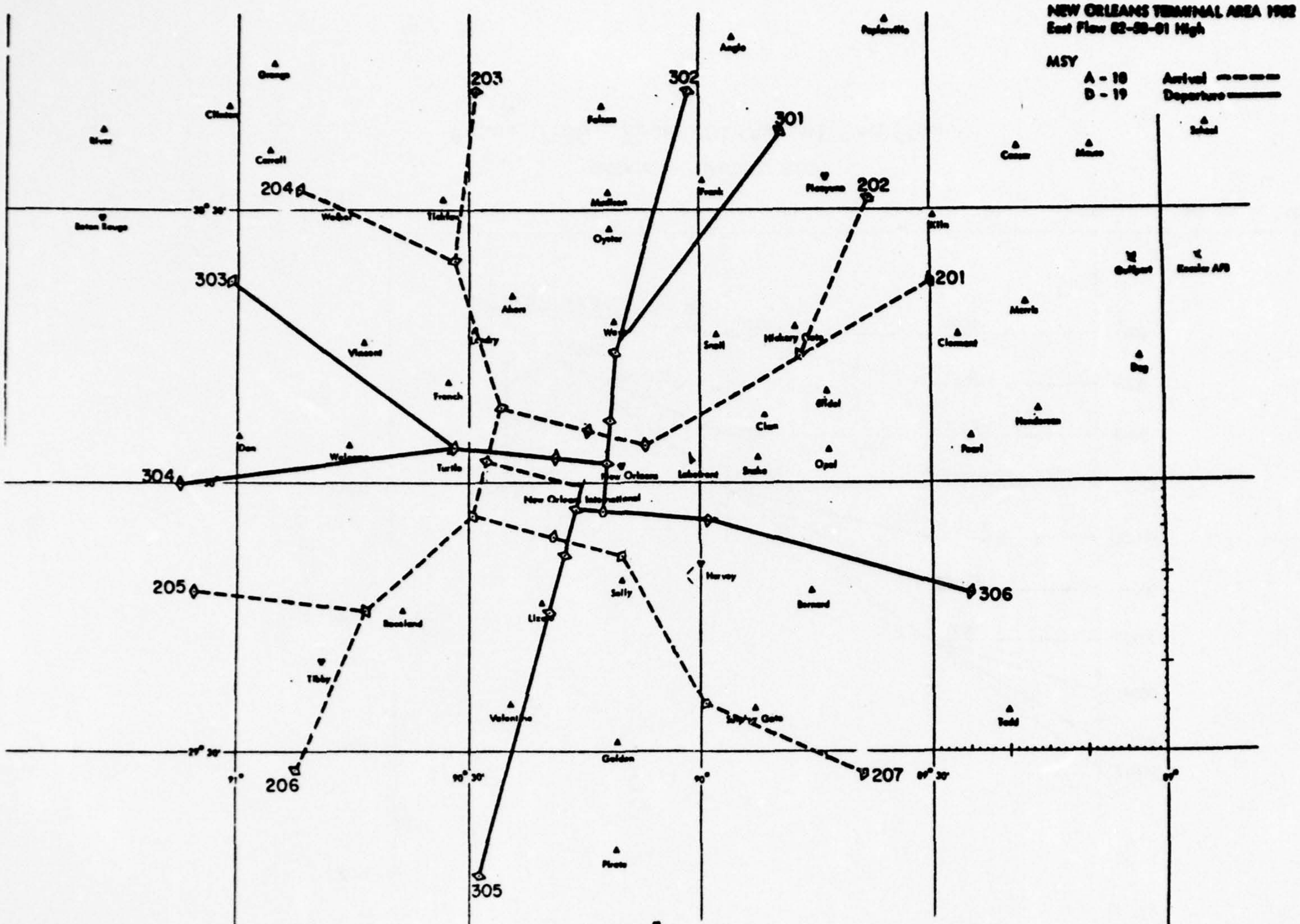


Figure 7.37 New Orleans Terminal Area - Post-1982 VNAV Routes, East Flow

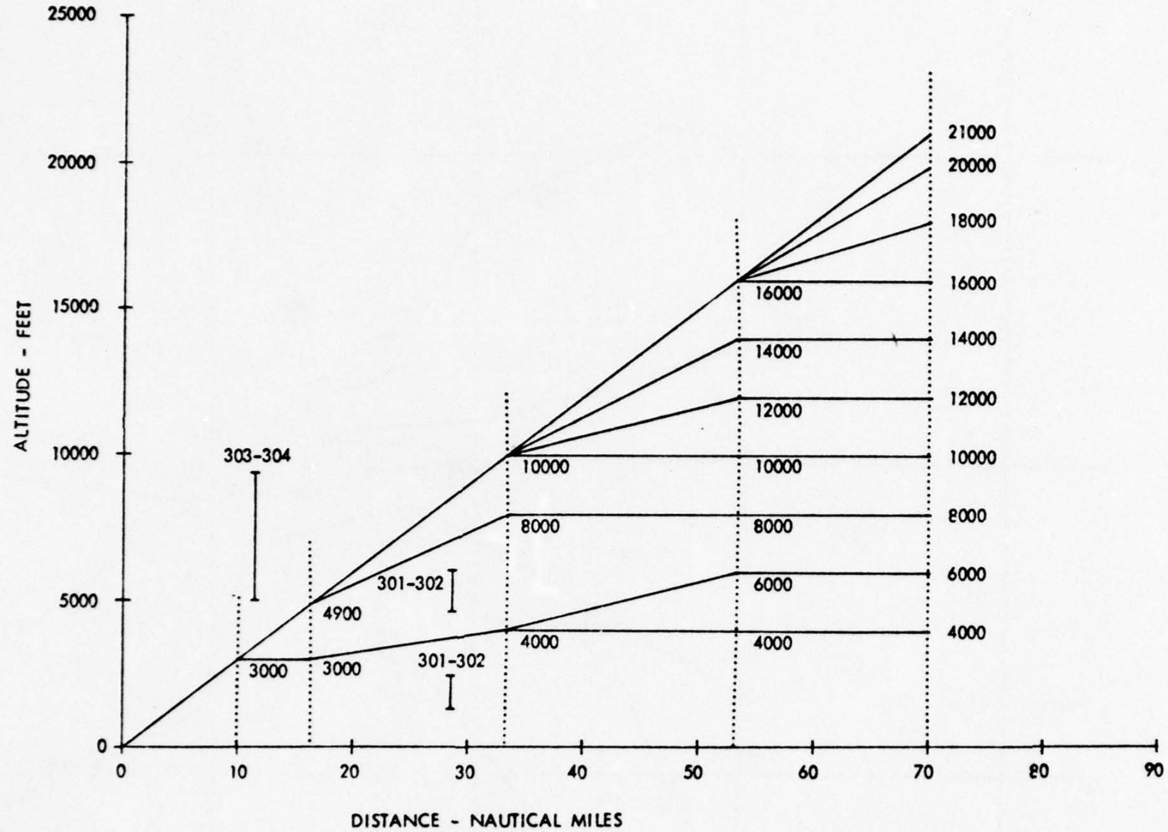


Figure 7.38 Route 201 (Arrival) East Flow

TABLE 7.4 Fixed Gradient VNAV Analysis

AIRCRAFT	CATEGORY	WEIGHT	Time Penalty (minutes) Climb Angle				Fuel Penalty (pounds) Climb Angle			
			2°	3°	4°	5°	2°	3°	4°	5°
DC-9-30	Regional Transport (2 Engine)	90,000#	0.55	0.32	0.18	0.12	77	36	16	5
DC-8-63	Intercontinental Transport (4 Engine)	300,000#	0.40	0.18	--	--	140	46	-	-
DC-10-10	Wide Body (3 Engine)	400,000#	0.45	0.20	0.06	--	204	105	66	-

An analysis was performed to determine the fuel and time impact of alternative transition/terminal descent procedures. The conventional long range descent procedure, which may be conducted with or without VNAV guidance, was evaluated and compared with two alternative high speed descent procedures, one of which may only be conducted if VNAV guidance is available. Figure 7.39 illustrates the situations analyzed. The dashed line from 25,000 feet to 10,000 feet represents the terminal design criteria descent slope of 300 ft/nm between waypoints. The solid line is the standard 250 knot (IAS) descent procedure for the DC-10. Note that there is an initial deceleration period at 25,000 feet from 340 to 250 knots. The two dotted lines represent high speed descent procedures for the DC-10. The high speed descent initiated at the start-descent waypoint is representative of the 2D RNAV situation, while the later high speed descent may be achieved given VNAV capabilities. In order to fly the high speed VNAV descent, the pilot must know the level deceleration distance required for his aircraft to achieve 250 knots at 10,000 feet at zero distance to go to the waypoint. His VNAV computer is then given an along track offset of this amount of deceleration distance. The high speed descent gradient value is entered into the VNAV computer and the aircraft remains at cruise altitude until the high speed VNAV gradient is intercepted. A deceleration period at 10,000 feet is provided for both the high speed VNAV and RNAV descent. Table 7.5 shows the fuel and time comparisons of these descent cases. A constant rate of descent case (not shown) has also been evaluated and presented in the table. The net effect of the high speed descents is a significant savings in time, but at the cost of additional fuel requirements.

As discussed in the previous paragraphs the economic penalty associated with flying a fixed gradient climb or descent compared to an optimum profile can be significant. An unrestricted climb is always more economical than a fixed gradient which is less than the optimum. Likewise, an optimum descent schedule employing high speed descent above 10,000 ft. is always more economical than adhering to a fixed gradient which is less than optimum. Actually, a high speed descent is more economical in time, although it uses more fuel than a lower gradient slower speed descent. The saving in time more than compensates for the extra fuel used if overall economic impact is considered.

Table 7.5 RNAV and VNAV Descent Comparisons

(DC-10-10, 280,000#, ISA)

	Time (min)	Fuel (lb)	Comparison with Baseline Descent	
			Time Benefit (min)	Fuel Benefit (lb)
Baseline Descent Case VNAV Fixed Gradient Descent (Approximately 300 ft/mile)	10.52	618		
High Speed RNAV Descent (Initiate high speed descent upon waypoint passage, decelerate at 10,000 ft.)	8.93	1057	1.59	-439
High Speed VNAV Descent (Set up along track offset for deceleration at 10,000 ft and VNAV gradient; intercept VNAV path after waypoint passage)	8.30	1031	2.22	-413
RNAV Descent 3000 ft/min., 340 KIAS Initiate Descent at Waypoint	8.88	1075	1.64	-457

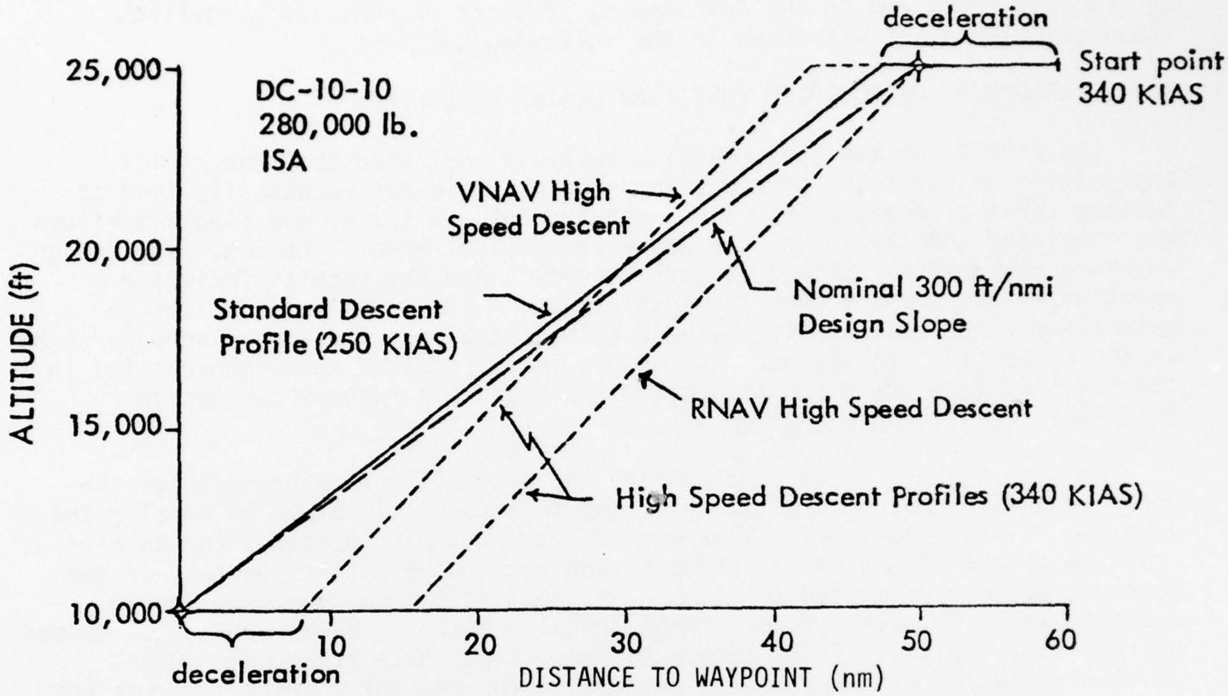


Figure 7.39 Descent Procedure Alternatives

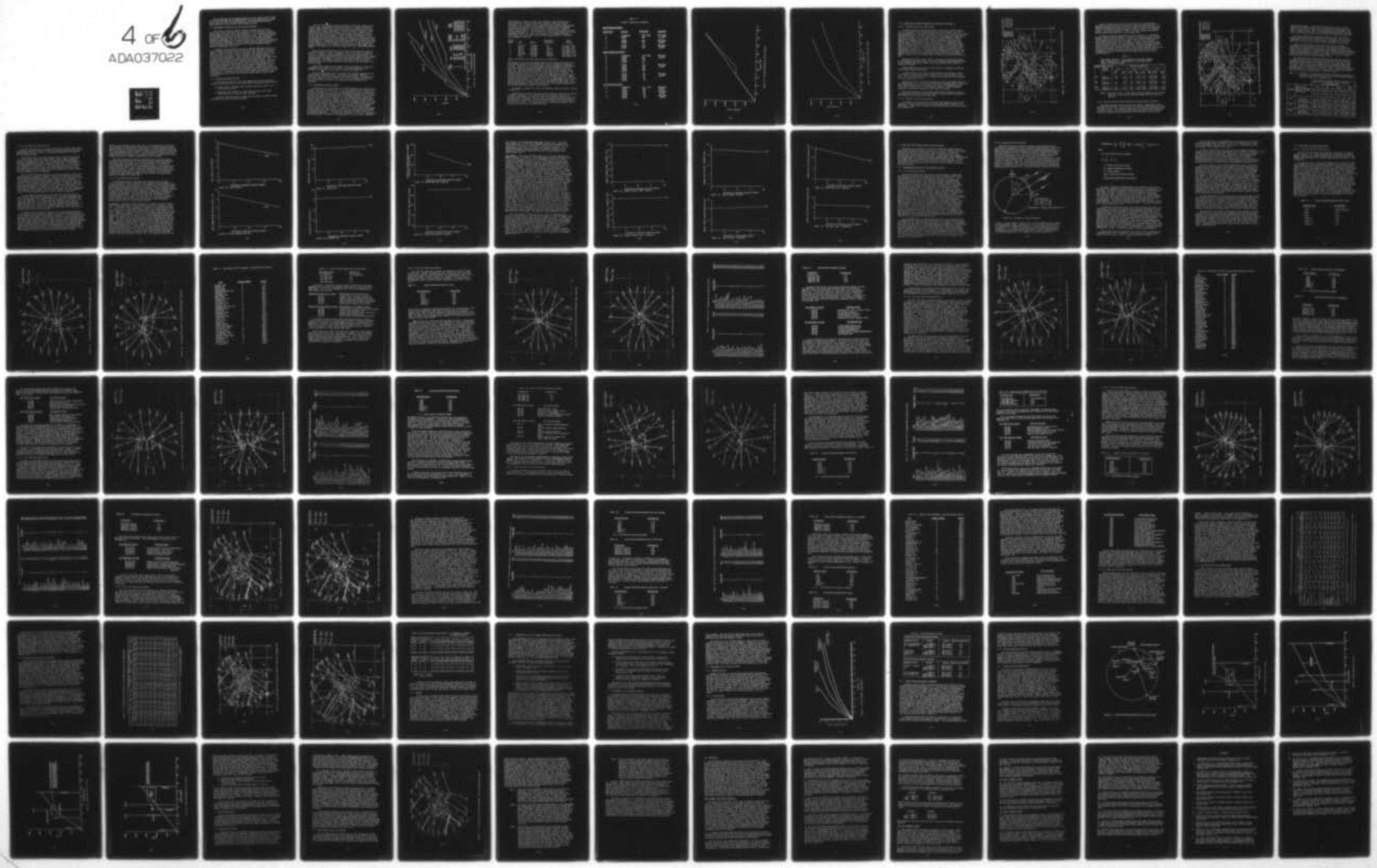
If fuel is the primary concern, a slower nominal descent should be used. It is apparent from the user's viewpoint that VNAV procedures and routes should be designed to provide the shortest path, coupled with the optimum gradient for a given aircraft on a given day.

Since the use of fixed gradient VNAV routes would result in user economic penalties, the only desirable utilization of such routes would be to increase airspace capacity over that available with 2D routes or to provide some unique air traffic control procedure which would lead to increased terminal area operation rates. Although VNAV "tubes" occupy less airspace, under some conditions, than blocked altitudes, it was determined that utilization of VNAV "tubes" would be warranted only rarely in terminal area designs to provide savings in usable airspace (see Appendix A). In addition, NAFEC controllers attempted to incorporate a "stacked Route" concept in the vicinity of the final approach maneuvering area in order to increase arrival rates. Their analysis of the stacked route concept (Appendix E) indicates that they could find no ATC benefit for this procedure. Consequently, the Task Force design concept for fixed gradient VNAV routes was modified to a vertical envelope concept within which pilot-selected optimum VNAV gradients can be utilized.

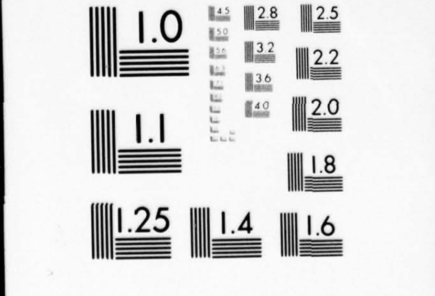
AD-A037 022 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
TERMINAL AREA DESIGN - ANALYSIS AND VALIDATION OF RNAV TASK FOR--ETC(U)
OCT 75 E D MCCONKEY , W H CLARK DOT-FA72WA-3098

UNCLASSIFIED FAA-RD-76-194 NL

4 OF 6
ADA037022



ADA037022



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

The problems that were encountered both by the user and by the ATC system in the use of the RNAV and the VNAV terminal area design guidelines as stated by the Task Force led to the development of a set of modified guidelines. These guidelines are discussed in the following sections.

7.4 DEVELOPMENT OF MODIFIED POST-1982 DESIGN GUIDELINES

The results of the user benefits analysis indicated that the strict application of the Task Force design principles did not necessarily lead to optimum terminal designs from a user standpoint. A set of modified guidelines was developed and applied to the New York terminal area. The resulting design was then analyzed for impact on user economics and the results indicated a substantial improvement over the initial design [3]. The modified design guidelines were subsequently reviewed with controllers and supervisory personnel at the respective FAA regions, and the comments received were incorporated in the final designs described in Section 7.5.2 and the recommended design guidelines described in Section 8.

An analysis of the terminals which had a negative RNAV benefit for the users indicated that generally one of two factors was involved in causing the penalty. Either the traffic flow was such that it was necessary for an aircraft to go out of its way in order to conform to the octant concept, or the aircraft was not permitted to climb or descend at its optimum rate due to crossing route considerations. These crossing route problems were often caused by requiring the aircraft to adhere to the octant route structure. One additional factor was found to be evident in the metroplex areas. It was not possible to use the box pattern on both sides of the final approach path in the terminal maneuvering area because to do so would generate conflicts with other airport traffic in the vicinity of the airport. Consequently, some new design guidelines were developed which based the terminal route structures on traffic flow and vertical profile attainment rather than conformation to the octant design. In addition, provisions for establishing conflict-free areas in the terminal maneuvering areas for metroplex airports were included in the guidelines.

7.4.1 Arrival and Departure Areas

In analyzing the results of the route length and altitude restriction analysis it was found that the two primary factors causing user penalties were:

- Longer routes in metroplex areas caused by requiring traffic to go to a particular octant.

- Excessively long segments of routes that were under an altitude restriction due to a crossing route situation.

In order to reduce the effect of these penalty sources, two major changes were made to the Task Force design concept.

The first major change involved the design of the octant overlay on the terminal area. The design of the routes in the plan view was initiated by using an octant pattern and aligning the octants to coincide with the major enroute traffic flows as depicted on a traffic distribution diagram. Octant boundaries are located near the major traffic flow lines so that arrivals may use the area on one side of the octant boundary and departures the area on the other side of the boundary. Should it happen that some major flows do not align well with an octant boundary, then the sizes of other octants can be adjusted to produce better octant boundary alignment with the major traffic flow directions. Consequently the octants become arrival and departure sectors because they are no longer necessarily of equal size. In some circumstances it may be desirable to add or delete sectors depending on the terminal area. However, eight sectors, 4 arrival and 4 departures, are a reasonable beginning point.

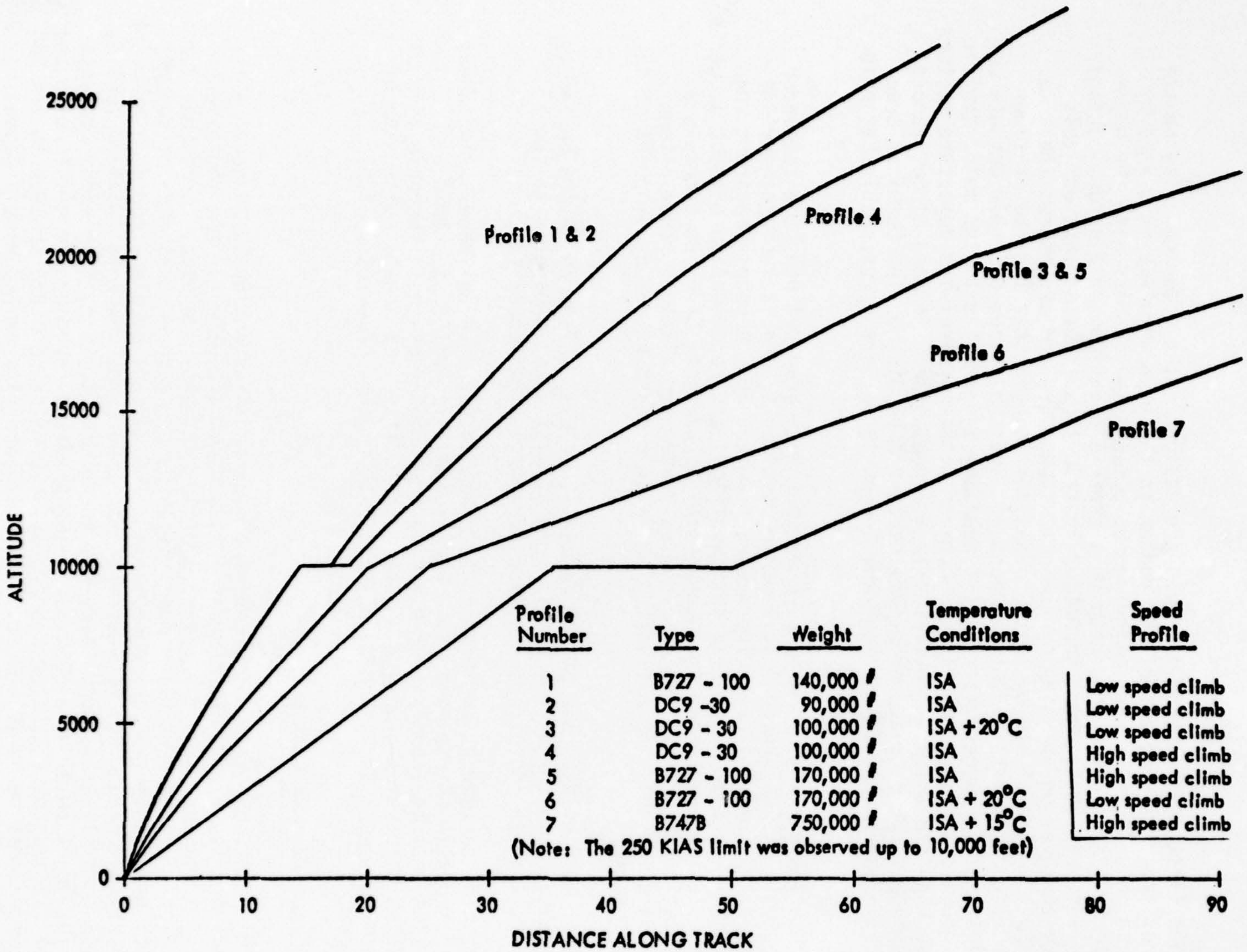
Once the arrival and departure sectors have been defined, the remainder of the route design proceeds in a manner similar to the Task Force model of Section 3. However, if some improvements in the design become apparent then the flexibility associated with this modified Task Force design concept suggests that the design be changed to incorporate improvements based on operational considerations. The problem of crossing routes and altitude restrictions should be given only minimal attention in this phase of the development of the modified design.

Some holding airspace at the feeder fixes was considered in the design to accommodate up to three or four aircraft at altitudes comparable to the altitude at which the aircraft nominally crosses the feeder fix.

Special considerations have to be given to the terminal maneuvering area traffic flows in metroplex areas. Conflicting flow patterns should be eliminated from the terminal maneuvering area route designs. The objective of this first phase of the design effort is to create a reasonable plan view of the terminal route structure of all airports for which routes will be developed.

7.4.2 The Vertical Envelope Concept

The next step in the development of the modified design is to develop the vertical profile view of each route. As a first estimate for the route vertical profile, a standard set of vertical profile gradients are used. Gradients for the modified routes were based upon the performance characteristics of several aircraft types under varying conditions. The descent gradient for each aircraft was nearly a constant at 300 feet/mile for long range descents (minimum fuel descent) from all altitudes. However, for aircraft making high speed descents above 10,000 ft (minimum time desent) the gradient increases to 400 ft/mile and a level altitude deceleration segment of 8-10 nm is required to slow to the 250 knot speed limit below 10,000 ft. The climb profiles varied widely depending on aircraft type, ambient temperature, aircraft weight and climb airspeed. Several typical profiles are shown in Figure 7.40. It can be seen that several of the profiles are quite similar. For example the medium weight DC9 (90,000#) and the medium weight B727 (140,000#) have identical low speed climb profiles at standard temperatures. The heavy DC9 (100,000#) at ISA + 20° C temperatures and the heavy B727 (170,000#) at ISA temperatures also have similar low speed



Profile Number	Type	Weight	Temperature Conditions	Speed Profile
1	B727 - 100	140,000 #	ISA	Low speed climb
2	DC9 -30	90,000 #	ISA	Low speed climb
3	DC9 - 30	100,000 #	ISA + 20°C	Low speed climb
4	DC9 - 30	100,000 #	ISA	High speed climb
5	B727 - 100	170,000 #	ISA	High speed climb
6	B727 - 100	170,000 #	ISA + 20°C	Low speed climb
7	B747B	750,000 #	ISA + 15°C	High speed climb

(Note: The 250 KIAS limit was observed up to 10,000 feet)

Figure 7.40 Typical Aircraft Climb Profiles

climb profiles. Finally, a heavy B727 (170,000#) climbs slightly better than a heavy B747 (750,000#) under high temperature and high airspeed conditions. As a consequence three separate vertical gradients were selected for the vertical profiles. These gradients were based upon the gradients achieved for each type of aircraft at three altitude levels - 10,000 ft, 18,000 ft and 25,000 ft. The following is an index of aircraft profiles used in the gradient analysis. Aircraft profiles 1 and 2 were selected for the high performance profile, 3, 4 and 5 were selected for the medium performance profile and 6 and 7 were used for the low performance profile. The results are presented in Table 7.6.

Profile Number	Type	Weight	Temperature Conditions	Speed Profile
1	B727-100	140,000#	ISA	Low speed climb
2	DC9-30	90,000#	ISA	Low speed climb
3	DC9-30	100,000#	ISA+20°C	Low speed climb
4	DC9-30	100,000#	ISA	High speed climb
5	B727-100	170,000#	ISA+20°C	Low speed climb
6	B727-100	170,000#	ISA+15°C	High speed climb
7	B747B	750,000#	ISA+15°C	High speed climb

/Note/ The 250 KIAS limit was observed up to 10,000 feet.

The gradients for the low performance profile and the high performance profile were chosen to define the conventional RNAV vertical envelope for departure aircraft. Additionally, a high performance vertical envelope was designated as the region between the medium performance and high performance profiles in Table 7.6. The high performance departure envelope is used on those routes where some specified minimum achievable vertical profile is necessary for the aircraft to remain free of conflicts from other RNAV routes in the area. In addition, the high performance route must have a demonstrated economic benefit for the aircraft using the route. This may take the form of either a shorter distance to the periphery of the terminal area or an improvement in the altitude restriction condition that was imposed on the corresponding RNAV route. The descent envelope was selected to be a single 300 ft/mile gradient below 10,000 ft and the region between a 300 ft/mile gradient and a 400 ft/mile gradient with a 10 nm level deceleration segment above 10,000 ft.

The vertical envelopes for arrival and departure routes are shown in Figures 7.41 and 7.42.

On the vertical profile views the crossing routes are marked and the desired altitude or altitudes of the crossing route are indicated. Conflicts in are easily identified on the profile view of the route when the altitude of the crossing route is depicted. Conflicts may be resolved by moving the routes in the horizontal view and affecting route length or using an altitude restriction on one or both routes. This design procedure is used on every terminal route and every crossing route in the terminal case.

TABLE 7.6

AIRCRAFT CLIMB PROFILE GRADIENTS

High Performance Profile

Aircraft No.	Altitude	Climb Rate	Composite
1	10,000 feet	565 '/mile	550 './mile
2	10,000	592	(5.18°)
1	18,000	347	350'/mile
2	18,000	344	(3.30°)
1	25,000	220	200'/mile
2	25,000	215	(1.89°)

Medium Performance Profile

Aircraft No.	Altitude	Climb Rate	Composite
3	10,000 feet	391 '/mile	400'/mile
4	10,000	509	(3.77°)
5	10,000	416	
6	10,000	311	
3	18,000	184	200'/mile
4	18,000	233	(1.89°)
5	18,000	188	
6	18,000	167	
3	25,000	83	100'/mile
4	25,000	144	(0.94°)
5	25,000	87	
6	25,000	78	

Low Performance Profile

Aircraft No.	Altitude	Climb Rate	Composite
6	10,000 feet	311 '/mile	300'/mile
7	10,000	267	(2.83°)
6	18,000	167	150'/mile
7	18,000	124	(1.41°)
6	25,000	78	100'/mile
7	25,000	96	(0.94°)

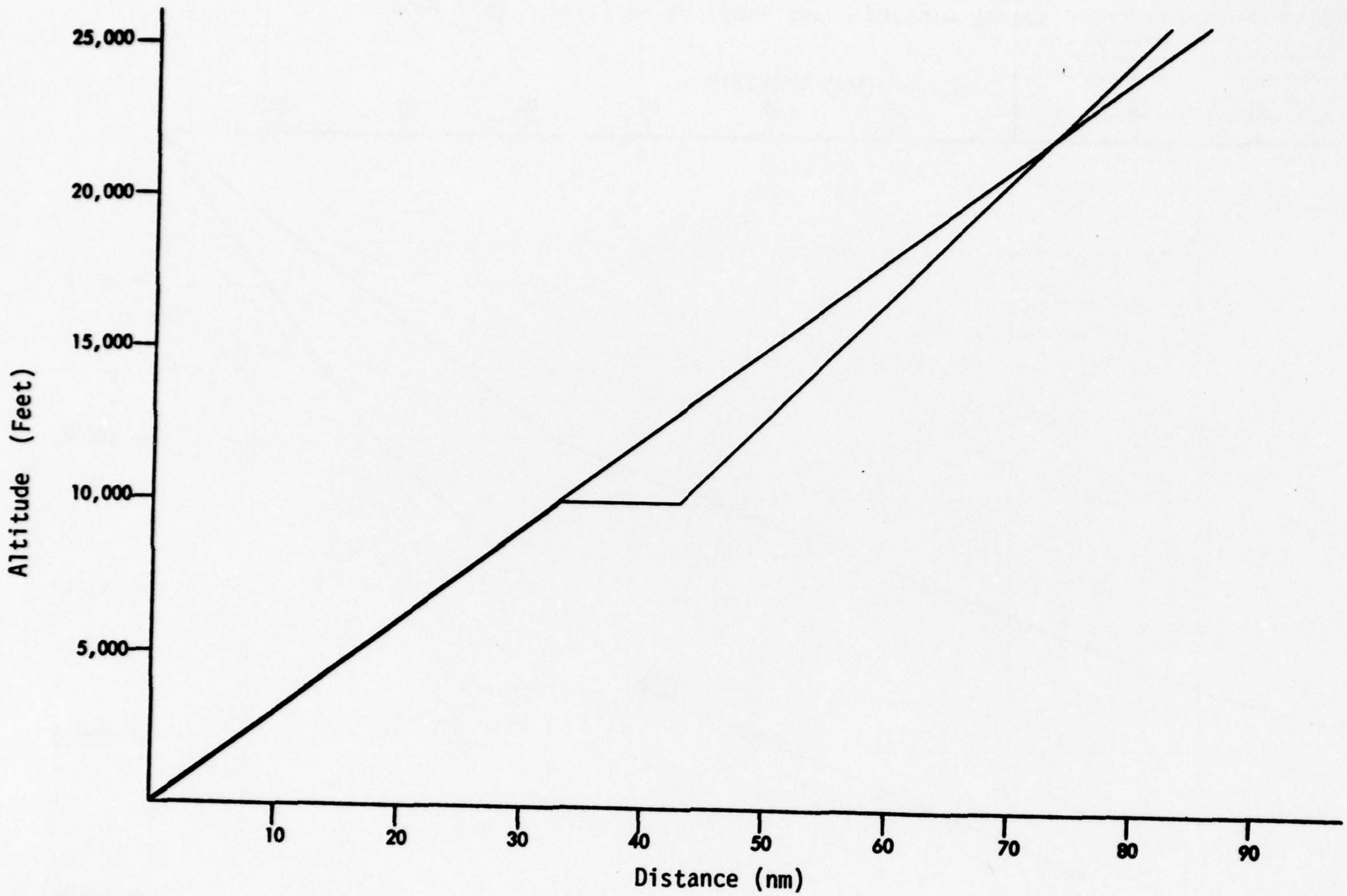


Figure 7.41 Vertical Envelope for Arrival Routes

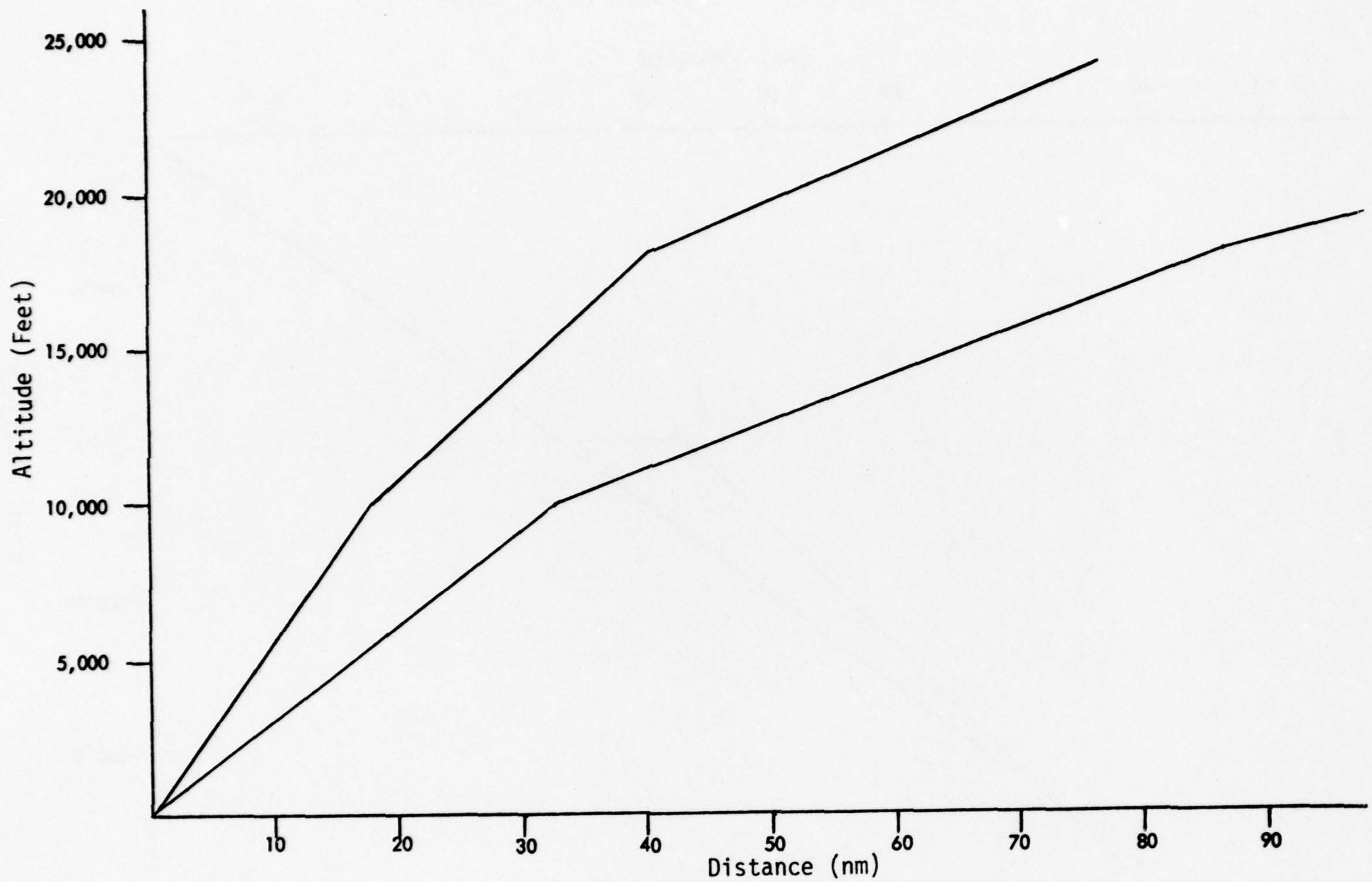


Figure 7.42 Vertical Envelope for Departure Routes

7.4.3 Application of Modified Guidelines to the New York Design

7.4.3.1 The Modified New York RNAV Design

The modified design technique was applied to New York, the most complex case, as an example of the improvement that could be achieved for the user. If this were beneficial then it would indicate that other terminal areas could also be changed beneficially. Terminal route designs for three major New York airports are shown in Figure 7.43. All routes are based on 2D procedures. VNAV procedures can be used on these routes as well, if desired by the user (see Appendix A). Kennedy arrivals J201, J204 and J205 closely approximate the Bohemia, Empire and Southgate arrivals in current use. In addition, routes J202 and J203 serving arrival traffic from the north and northeast have been added. La Guardia arrivals use routes that are similar to the Carmel, Penwell and Robbinsville arrivals. Traffic from the northeast travel north of the Kennedy and La Guardia traffic and merge with northwest arrivals north of the present Monroe holding area. The west arrivals for Newark can use either the RNAV Budd Lake arrival or route E204 which passes nearly over the Solberg VORTAC. Arrivals from the southwest pass to the west of the Princeton holding area.

Departures from each airport travel in parallel or near parallel routes to the northeast near Belle Terre, to the west northwest toward Huguenot VORTAC, to the southwest near Solberg VORTAC and to the south near Colts Neck and Robbinsville VORTACs.

Kennedy departures can proceed to the terminal area boundary essentially without any altitude restrictions.

La Guardia arrivals can achieve a near optimum arrival profile. Route L202 requires a slight restriction for about 8 nm to clear the Empire holding area. All La Guardia departures can proceed in the optimum vertical departure envelope without restriction.

Newark arrivals from the north and south must have an altitude restriction for approximately 15 nm. Arrivals over Budd Lake can proceed without restriction. Newark RNAV departures to the northeast (E301) have a considerable altitude restriction of about 40 nm at an altitude of 10,000 ft. The other Newark departures can proceed unrestricted to the terminal boundary.

The routes developed in this modified design effort resulted in arrival and departure routes which served major traffic flows and which had optimum or near optimum vertical profiles in most cases.

7.4.3.2 Analysis of the Modified Design

The routes of the modified New York design were analyzed using the route length and altitude restriction analysis program described in Section 3 and Reference 3. Results were compared to the current New York terminal area design for southwest flow.

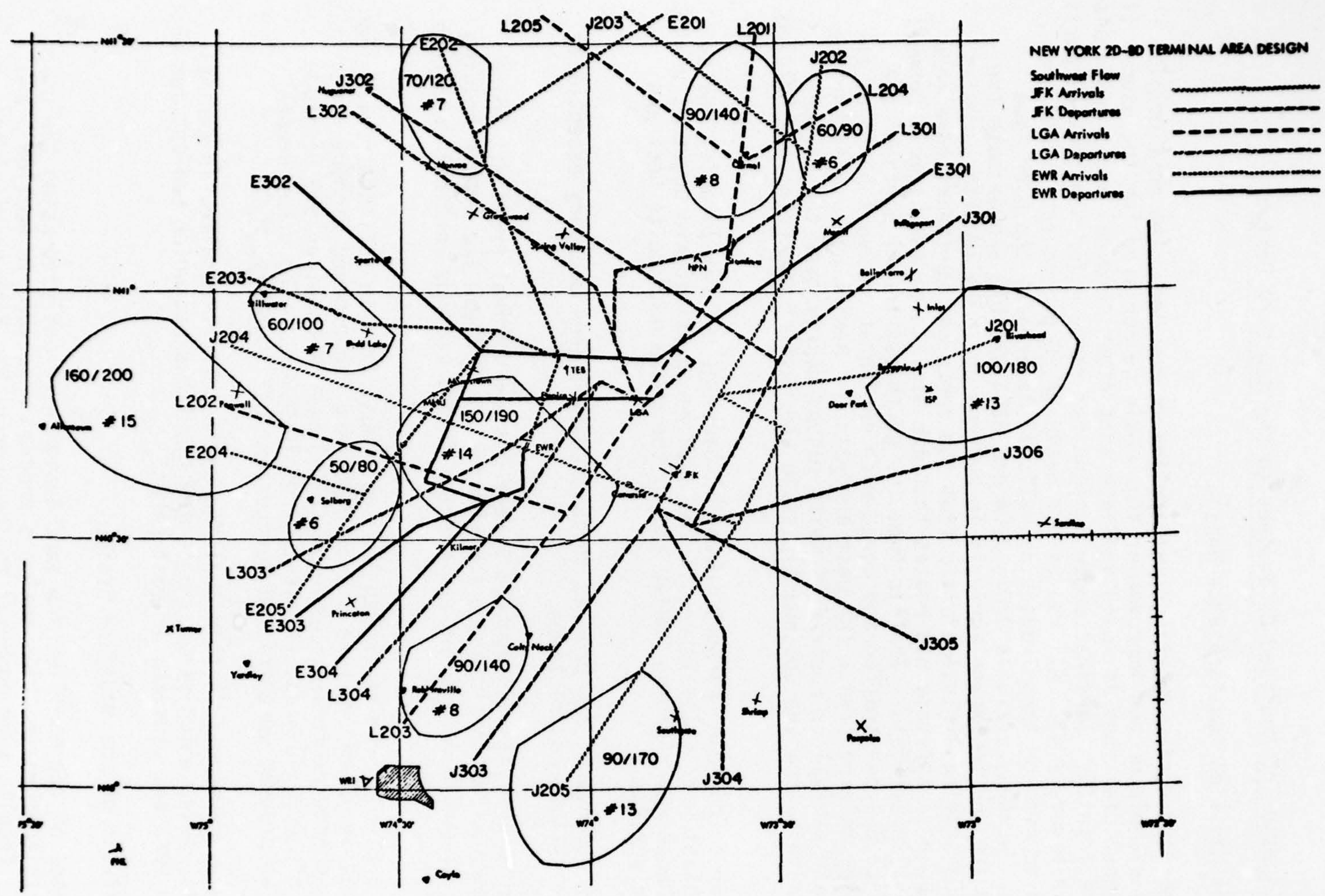


Figure 7.43 Application of Modified Guidelines to Initial New York Design

Table 7.7 presents the results of this analysis for the RNAV routes. The modified design results are contained in the row labeled "modified". For comparison purposes the results of the route length and altitude restriction analysis for the original New York design (noted as "strict"), are presented as well. The results presented in Table 7.7 strongly support the modified design as being more beneficial to the airspace user.

In every case the modified design has made a penalty, or a non-benefit, become a definite positive benefit. The use of the modified design in other terminal areas can produce additional benefits over those obtained with the strict application of the Task Force model. This will occur since the modified design procedure lifts the constraint imposed by the octant concept of the location of routes and route endpoints. Certainly the modified design need be no worse than the octant design, because they can be identical if the octant design were the optimum design. By the same reasoning, the modified design can be no worse than the current VOR/radar vector route structure. Consequently, the use of the modified design should provide only zero or positive benefits.

TABLE 7.7

RNAV BENEFIT POTENTIAL - RNAV OPERATIONS IN NEW YORK TERMINAL AREA - SOUTHWEST FLOW - BASED ON MODIFIED TASK FORCE DESIGN CONCEPT FOR METROPLEX AREAS **

AIRPORT	Task Force Design Concept	Savings per Operation							
		DC-9		B727		DC-8		B747	
		Fuel (lb)	Time (Min)	Fuel (lb)	Time (Min)	Fuel (lb)	Time (Min)	Fuel (lb)	Time (Min)
JFK	Strict	-197	-1.14	-277	-1.10	-433	-1.09	-594	-1.10
	Modified	146	2.02	242	1.98	370	2.06	638	2.03
LGA	Strict	2	0.03	16	-0.05	-50	0.00	-152	-0.11
	Modified	282	3.37	439	3.43	722	3.43	1164	3.52
EWR	Strict	-141	-1.33	-199	-1.32	-294	-1.33	-468	-1.32
	Modified	188	1.31	179	1.38	367	1.41	650	1.48

**Note: The positive values in this table indicate a benefit to the airspace user; minus signs indicate those areas where the net effect was negative.

7.4.3.3 New York High Performance Departure Envelope Design and Analysis

The high performance design procedure was applied to departures from the three New York terminals, and was based on the initial modified design described in Section 7.4.3.1. The composite conventional and high performance RNAV routes are shown in Figure 7.44. The 200 number routes are arrivals, the 300 number routes are conventional RNAV departures and the 500 number routes are high

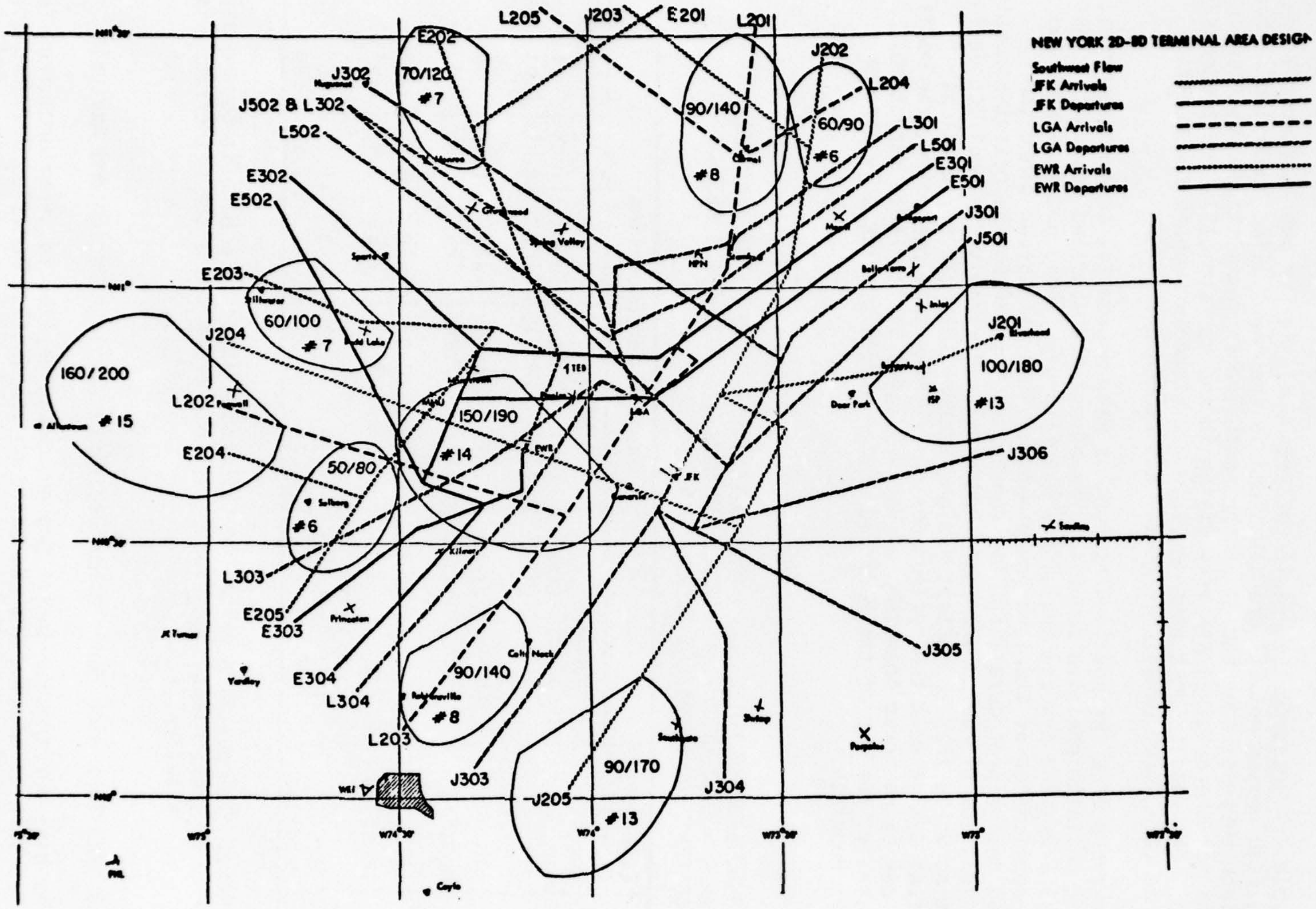


Figure 7.44 New York High Performance RNAV Terminal Area Design

performance departures. At Kennedy it was determined that a slightly shorter route to the northeast could be obtained by removing some of the dogleg in route J301 if a medium climb gradient could be achieved. This route is shown as number J501. The high performance departure route J502 also is considerably shorter than the 2D RNAV route J302 to the northwest.

The two La Guardia high performance departures L501 and L502 are slightly shorter than their counterparts, L301 and L302. Since the high performance routes are only slightly shorter, the benefits for the user would not be as significant as the distance improvement on route J502.

Some of the most dramatic user benefits occured for the Newark departures to the northeast on route E501. The altitude restriction for 40 nm that was necessary for route E301 has been removed from E501. Even though the two routes are of approximately equal length, the high performance route is more advantageous because of the removal of the altitude restriction. Route E502 from Newark is slightly shorter than route E302 as the dogleg has been removed from the high performance route.

The high performance routes were analyzed using the route length and altitude restriction analysis program, only applying traffic to the high performance routes rather than the RNAV routes of the conventional design. The results of the analysis were compared to the conventional RNAV route structure. Table 7.8 presents both the conventional and the high performance RNAV results for purposes of comparison. Both a time and fuel advantage were obtained for all three airports. The benefits for Kennedy and Newark are significant while the benefit for La Guardia is small.

TABLE 7.8 Comparison of per Operation Savings Using Conventional Departure Envelopes to per Operation Savings Using High Performance Departure Envelopes - New York - Southwest Flow

AIRPORT	Type of RNAV vertical envelope employed by departing aircraft	Benefits per RNAV operation based on improvement over VOR/vector routes							
		DC-9		B727		DC-8		B747	
		Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)
JFK	Conventional	146	2.02	242	1.98	370	2.08	638	2.03
	High Performance	226	2.74	350	2.67	543	2.75	910	2.69
LGA	Conventional	282	3.37	439	3.43	722	3.43	1164	3.52
	High Performance	289	3.43	449	3.50	738	3.50	1163	3.53
EWR	Conventional	118	1.31	179	1.31	367	1.41	650	1.48
	High Performance	171	1.74	246	1.68	472	1.84	828	1.92

7.4.3.4 Post-1982 Real Time Simulation

The real time simulation of the post-1982 New York Terminal [18] area was considerably different from the 1972-1977 and the 1977-1982 transition time period simulations [13]. Several of the major differences are discussed in the following paragraphs.

The southwest flow for New York-Kennedy shown in Figure 7.43 was used as a basis for the simulation route structure. The arrival and departure routes in the area east of the airport were modified by NAFEC based upon controller recommendations after initial simulation tests. The reasons for the modification are explained in Appendix E, Section E.3, of this report and in Appendix A of Reference 18. In essence, the area used for arrivals and departures to the east of the airport were exchanged in order to give the final controllers more flexibility in controlling arrival times by shortening the downwind leg of the approach.

In the transition period simulations, arrival and departure traffic was purposely held to a moderate increase in order to evaluate controller workload without the additional constraint of operating at maximum system capacity. Having established these workload patterns in the previous simulations, it was possible to evaluate system capacity effects and controller workload effects in the post-1982 route structure simulation. In order to reduce the constraint upon terminal area capacity that is imposed by the airport runways, Runway 22R at Kennedy was assumed to be relocated. This new runway was positioned sufficiently west of the existing Runway 22L such that simultaneous IFR approaches could be made to the two arrival runways on a non-interfering basis. All traffic used either 22L or 22R for arrival or departure.

The post-1982 simulation made use of various participation levels by radar vectored, RNAV and VNAV equipped aircraft. Initially independent VNAV routes for departures and "stacked" VNAV arrival routes were considered for use in the simulation. For reasons outlined in Appendix E, Section E.4, the independent VNAV routes were dropped from the simulation route structure during the data runs. Aircraft that were VNAV equipped were permitted to use VNAV procedures unless specifically requested otherwise. The routes were designed according to the vertical envelope concept described in Section 7.4.2 rather than the fixed-gradient concept.

In order to obtain a degree of realism in the radar displayed position of the aircraft, two features were added to the post-1982 simulation that were not included in the transition time period simulations. First, navigation error characteristics were added to the simulated aircraft so that some dispersion of the target from its nominal track would occur as the aircraft proceeded along its radar vector, RNAV or VNAV route. Radar vectored aircraft were given compass system, airspeed and flight technical error characteristics. RNAV and VNAV controlled aircraft were given VOR and DME system errors along with airspeed and flight technical error values. The second element of realism that was added in the post-1982 simulation was the use of two general aviation trainers (GAT) equipped with general aviation quality RNAV and VNAV computers.

The GATs were operated by qualified pilots to simulate general aviation aircraft operating in the New York Kennedy airspace. Aircraft position from the two GAT systems was electionically connected to the digital simulation facility (DSF) such that the aircraft appeared as targets on the controller's scopes just as the DSF-generated target aircraft. The controllers and pilots were in constant communication throughout the simulation exercises so that the pilot could respond to controller requests by maneuvering the GAT controls.

One final difference between the post-1982 and the transition period simulations should be noted. The post-1982 simulation used five controllers from field facilities in addition to the regular NAFEC staff controllers. The previous RNAV simulations used no field controllers. The field controller attitudes toward the use of RNAV/VNAV procedures in the terminal area shifted significantly in favor of RNAV from the beginning to the end of the simulation exercises. Detailed statistical analysis of these attitude shifts is contained in Reference 18. A qualitative assessment of the field controllers' attitudes toward RNAV/VNAV in actual terminal area operations is contained in Appendix E of this report.

7.4.3.5 Post-1982 Simulation Results

A considerable number of parameters were recorded during the data collection phase of the post-1982 real time simulation of the southwest flow at New York-Kennedy. Upon completion of the simulation activities the recorded parameters were analyzed statistically to identify significant changes in the data as RNAV and VNAV participation levels increased. A more complete breakdown of the simulation results by control position is contained in Reference 18. A summary of these results based on regression line analysis is contained in the following paragraphs. The regression equations respresented by the following figures are all significant at level 0.05. In certain cases only a single constant value is shown. For these cases the slope was not statistically significant at the 0.05 level and the data is best represented by the average value for all participation levels.

ATC Benefits Controller workload parameters are shown in Figures 7.45 and 7.46. The average number of radio contacts per aircraft are shown in Figure 7.45. In the radar vector environment an average of 5.82 contacts were made per aircraft while at 100% RNAV/VNAV participation the average number of contacts dropped to 3.72 contacts per flight for an overall 36% reduction in contacts. Likewise as depicted in Figure 7.46 the average communication time was reduced from 17.94 seconds in the 0% case to 10.40 seconds in the 100% case, indicating a reduction of 42% over the full range of RNAV/VNAV participation levels. In Figures 7.47 and 7.48 the average arrival and departure rates are shown. It can be seen that arrival rates increased slightly (3%) from 76.59 arrivals per hour in the 0% RNAV/VNAV case to 79.09 arrivals per hour at the 100% RNAV/VNAV participation level. Departures on the other hand showed no significant change from the average departure rate of 80.30 aircraft per hour at any participation level. The final-ATC related parameters that are presented indicate the percentage of the time that RNAV or VNAV clearances were broken by the controllers. The percentage of broken RNAV/VNAV clearances of the horizontal flight path are shown in Figure 7.49 while the broken VNAV gradient clearances are shown in Figure 7.50. These regression equations are

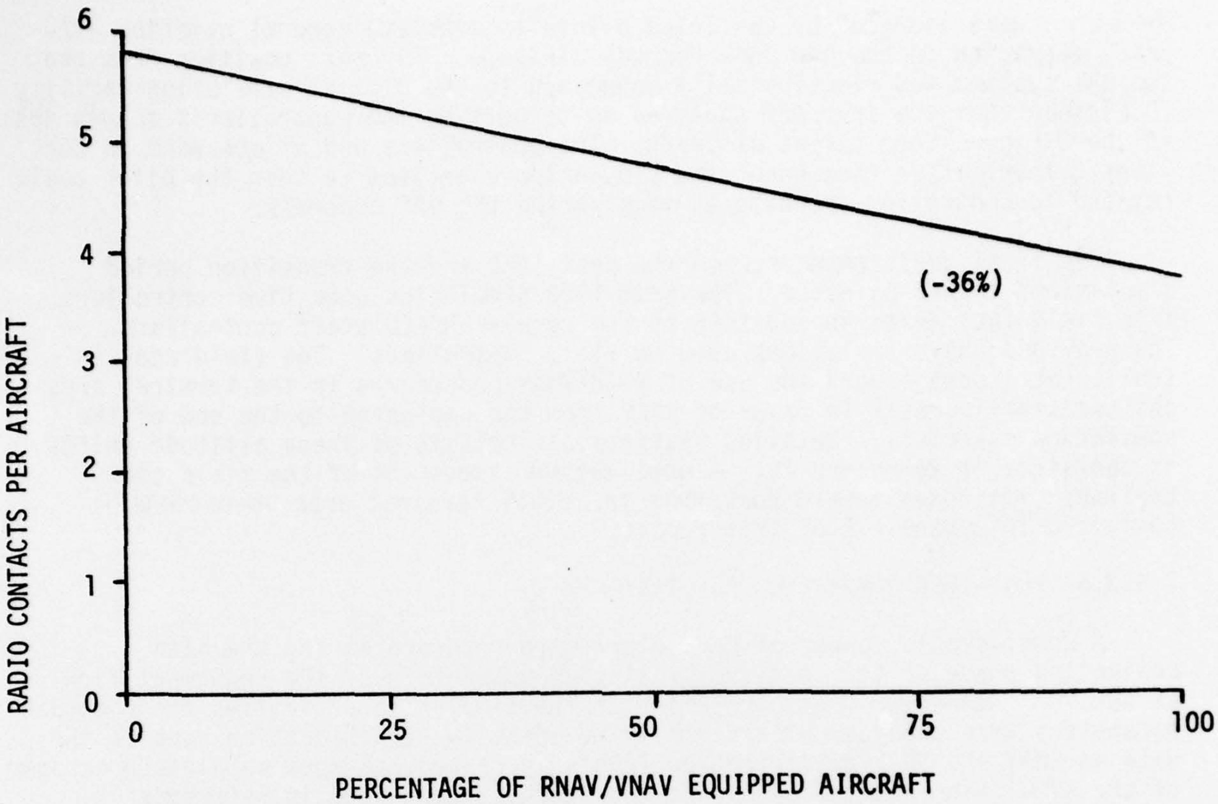


FIGURE 7.45 RADIO CONTACTS

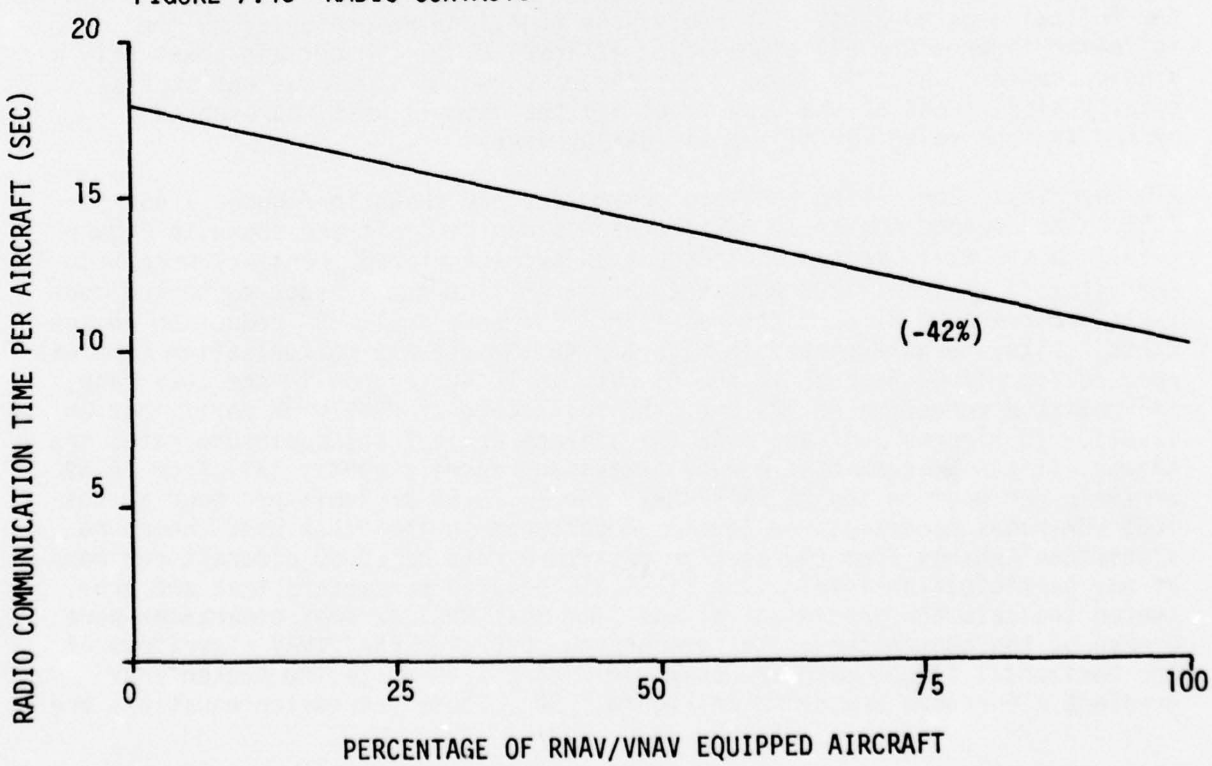


FIGURE 7.46 RADIO COMMUNICATION TIME

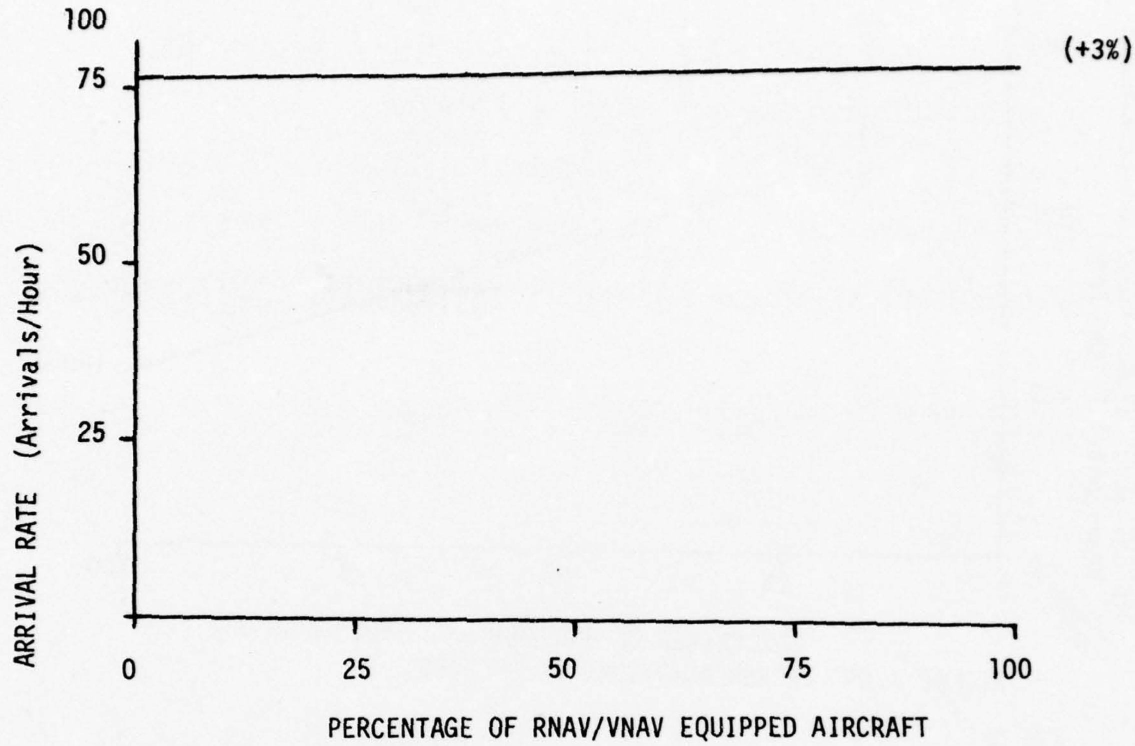


FIGURE 7.47 ARRIVAL RATE

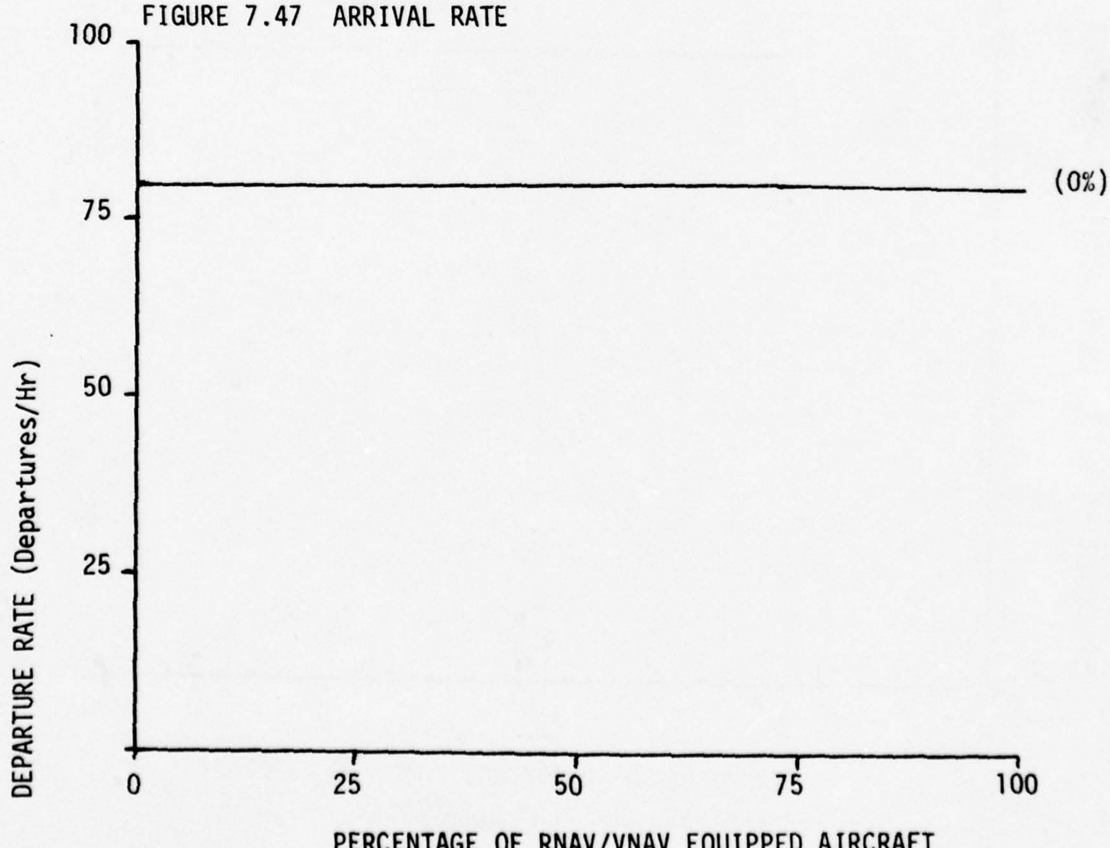


FIGURE 7.48 DEPARTURE RATE

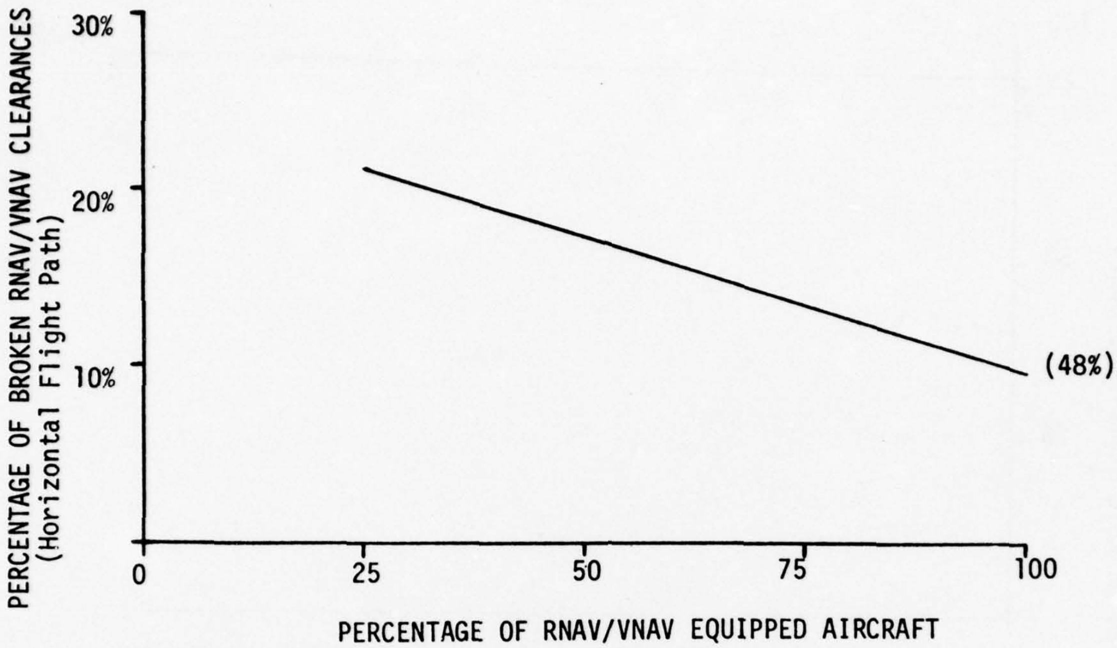


FIGURE 7.49 BROKEN RNAV/VNAV CLEARANCES

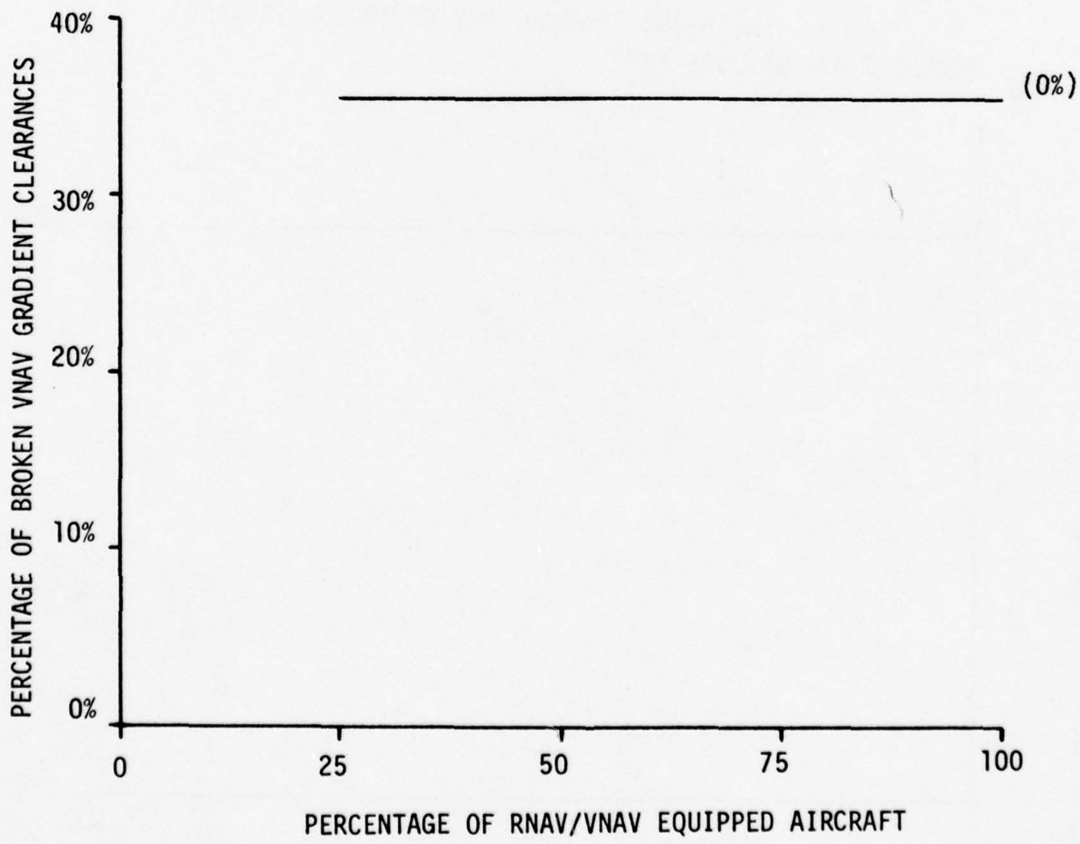


FIGURE 7.50 BROKEN VNAV GRADIENT CLEARANCES

valid from 25% to 100% RNAV/VNAV participation levels only. At the 25% participation level 18.63% of the RNAV/VNAV clearances were broken while at the 100% level 9.63% of the horizontal clearances were broken for a 48% reduction over the range of validity of the regression equation. The broken VNAV gradient clearances showed no significant changes from the average of 35.29% broken clearances over the valid participation level range (Figure 7.50).

User Benefits - The average distance flown for arrivals and departures is shown in Figures 7.51 and 7.52. Arrivals showed a reduction in flight miles of 3% from an average of 57.30 nm of 0% RNAV/VNAV aircraft to 55.53 nm at 100% area navigation equipped aircraft. Departures on the other hand showed no significant change in distance flown as RNAV/VNAV participation increased. The average distance flown for departures was 43.99 nm for all participation levels. Time in system, however, did change for both arrival and departing traffic. For arrivals the time in system improved 6% from 17.77 minutes to 16.65 minutes as the RNAV/VNAV equipped aircraft increased from 0% to 100%. This reduction in time in system is shown in Figure 7.53. The time in system for departures, however, increased by 8% as the percentage of VNAV aircraft increased from 0% to 100%. The 0% VNAV departure times were 10.55 minutes while the 100% VNAV departures required 11.35 minutes. This increase is pictured in Figure 7.54. The most plausible explanation of the increase in departure time in system is that departing VNAV aircraft climb at steeper gradients,and thus slower airspeeds,than do RNAV and radar vectored aircraft. Consequently, these aircraft leave the terminal area at slower airspeeds but higher altitudes than do non-VNAV equipped aircraft. The implications on user time and fuel benefits are not clear in this instance because the higher altitude of the VNAV aircraft at the terminal boundary indicates that the aircraft can operate for a longer distance at cruise altitudes which are more fuel efficient and faster than the lower gradient, higher airspeed climbs of the RNAV and radar vectored aircraft. The data is not sufficient in this case to make benefit judgement for either the VNAV or non-VNAV equipped user. The final user benefit parameter that is presented is the start point delay for both arrivals and departures (Figures 7.55 and 7.56). Start point delay for arrivals in the DSF is equivalent to holding in center (ARTCC) airspace prior to entering the terminal area. Start point delay for departures is equivalent to holding on the ground prior to take-off. Arrival start point delays exhibited a 34% reduction from 14.99 minutes to to 9.83 minutes as the RNAV/VNAV participation increased from 0% to 100%. No significant change in departure start point delays was observed as RNAV/VNAV participation increased. The departure delay averaged 6.38 minutes.

With the exception of departure time in system for VNAV departures which was discussed earlier, all ATC and user benefit parameters showed either no effect or improvement as RNAV/VNAV participation incrased. In particular, sizable reductions in controller workload (radio contacts and radio communication time) and broken RNAV/VNAV clearances were observed as the percentage of area navigation equipped aircraft increased. In addition arrival start point delays (center holding) were significantly reduced as the use of RNAV and VNAV increased. Small improvements in arrival distance flown, arrival time in system and arrival rates were noted with increased use of RNAV and VNAV. Departure statistics, except as noted previously with time in system, were generally unaffected by the increased use of RNAV/VNAV equipped aircraft.

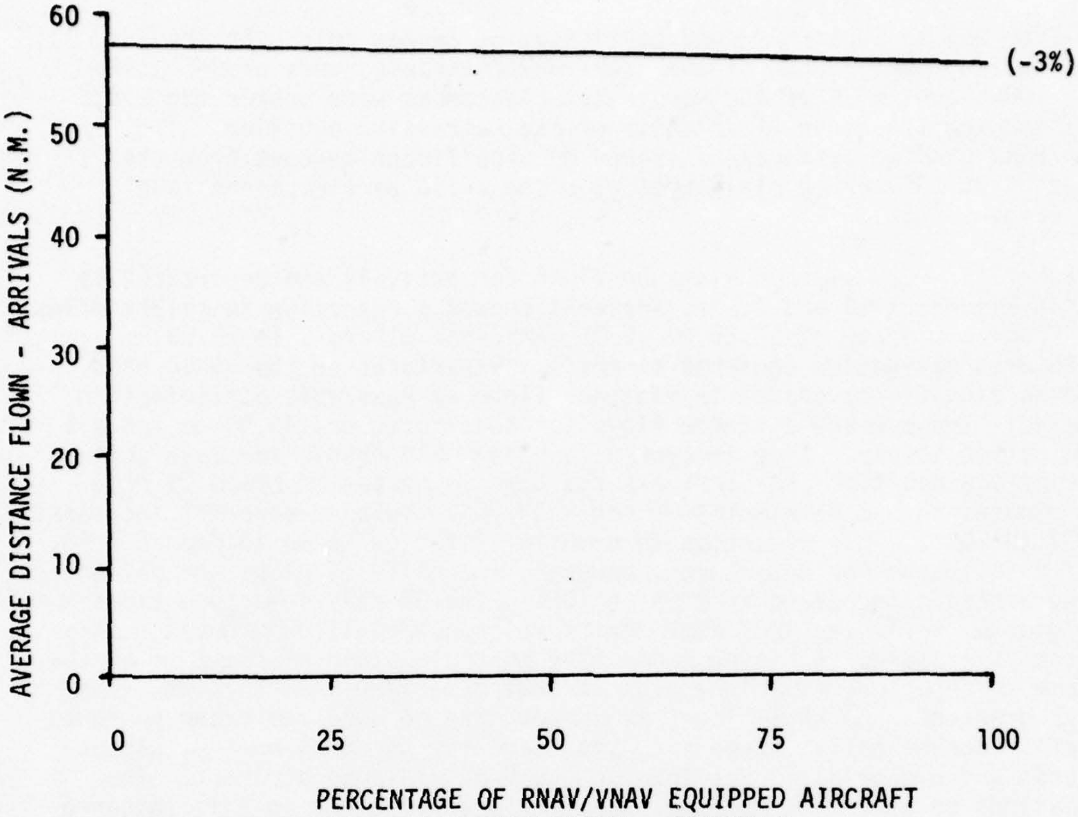


FIGURE 7.51 AVERAGE DISTANCE FLOWN - ARRIVALS

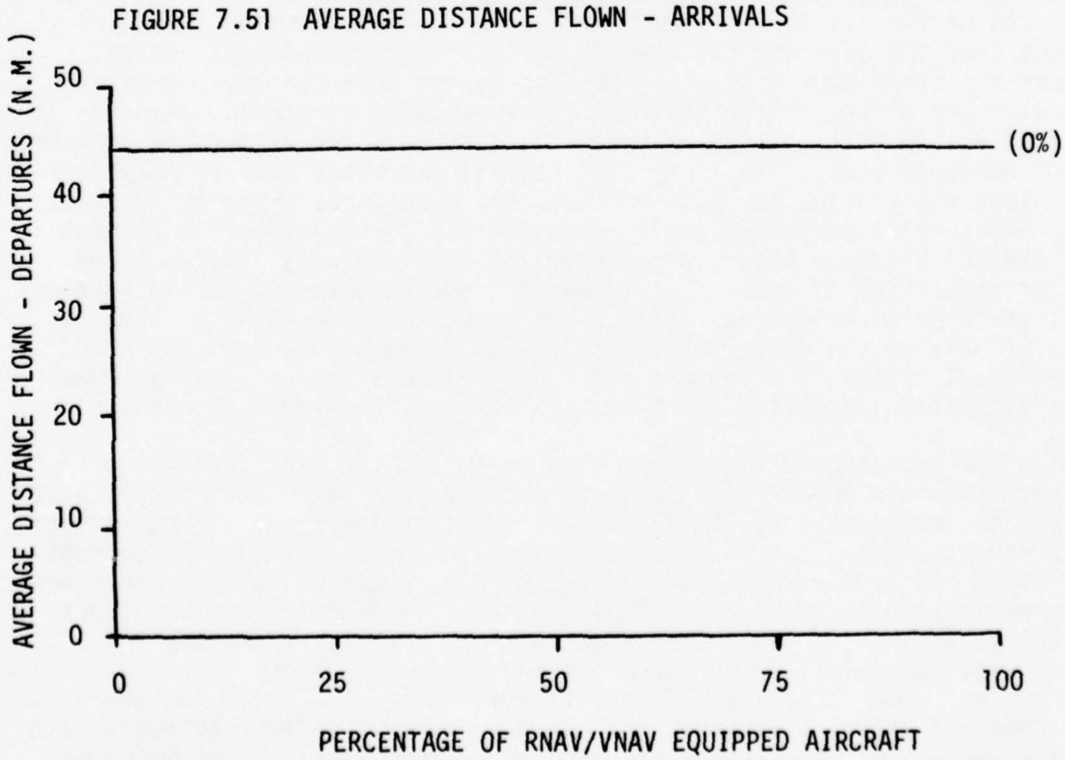


FIGURE 7.52 AVERAGE DISTANCE FLOWN - DEPARTURES

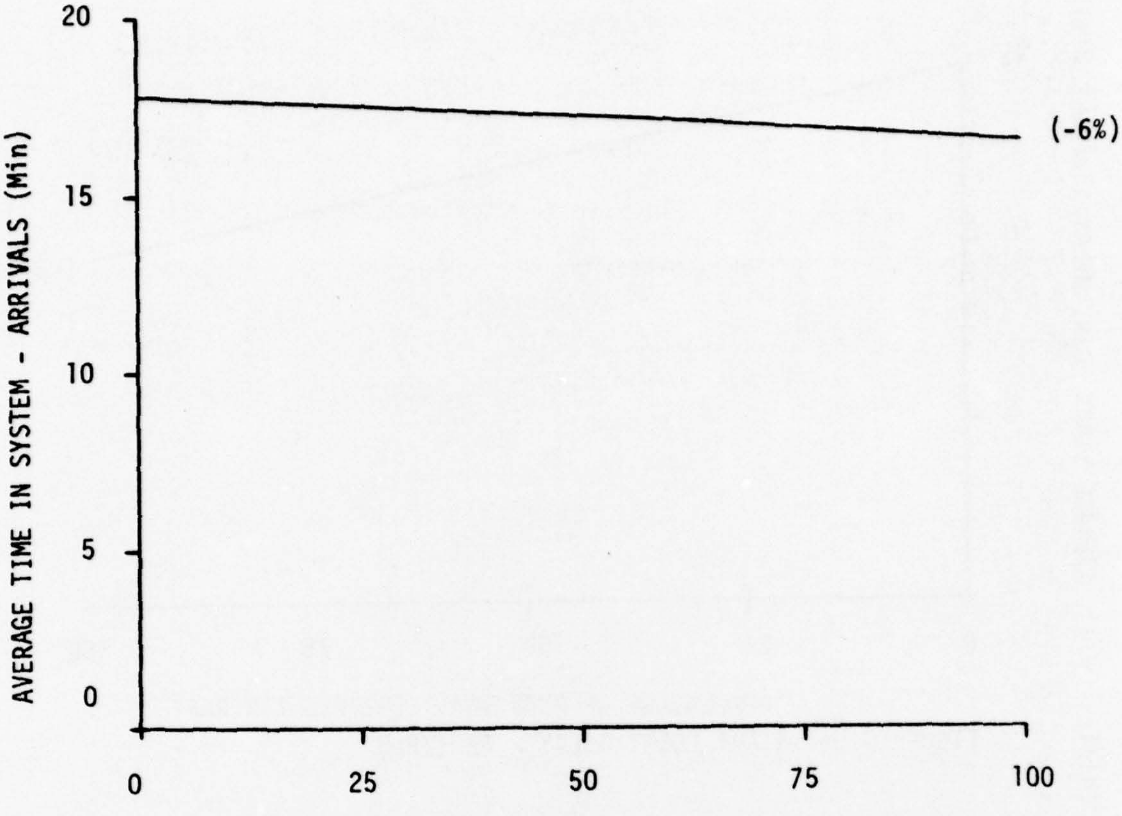


FIGURE 7.53 TIME IN SYSTEM - ARRIVALS

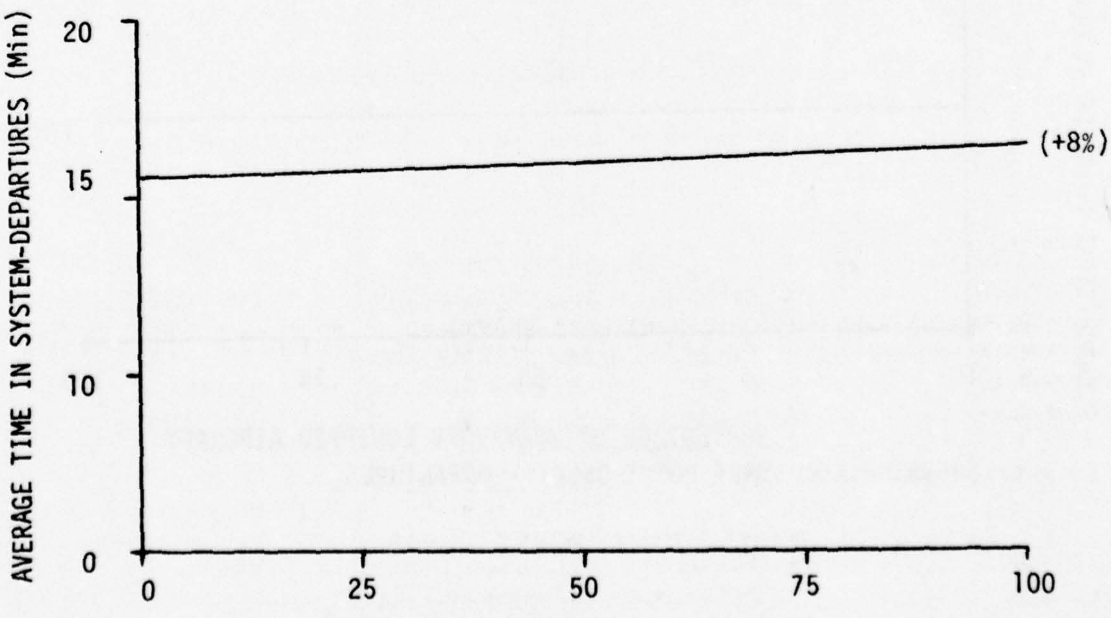


FIGURE 7.54 TIME IN SYSTEM - DEPARTURES

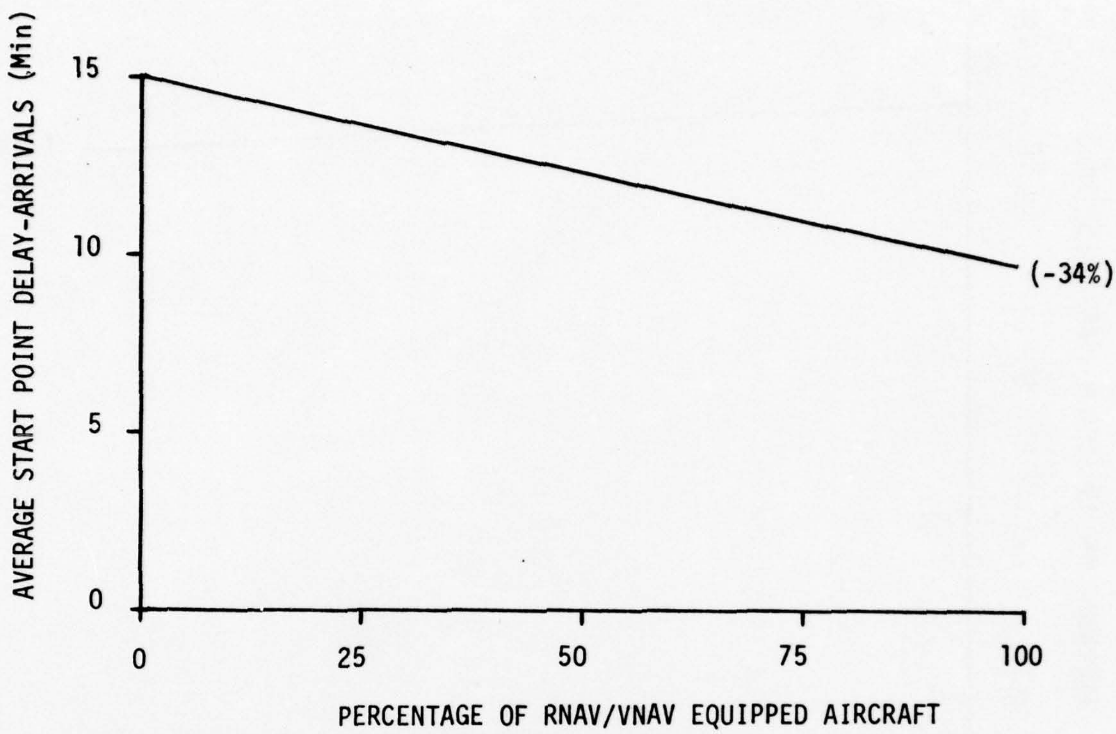


FIGURE 7.55 START POINT DELAY - ARRIVALS

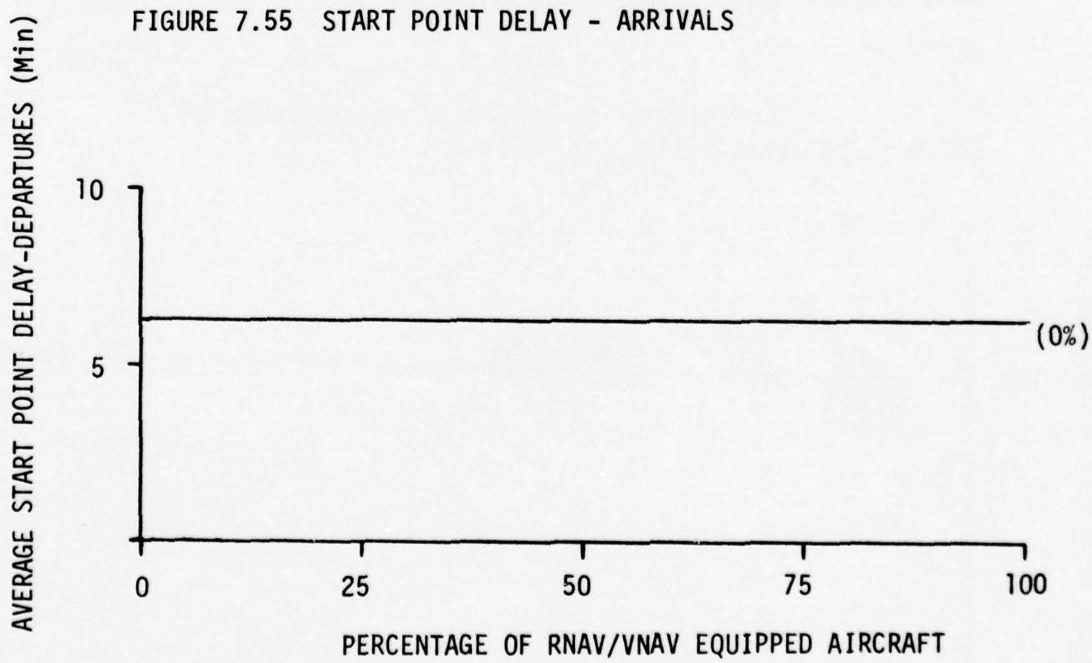


FIGURE 7.56 START POINT DELAY - DEPARTURES

7.5 FINAL POST-1982 TERMINAL AREA DESIGN APPLICATIONS

The results of the analysis in Section 7.4 definitely support the conclusion that the modified design for New York is clearly superior to the present VOR design and the Task Force terminal area model design. In addition, the selective use of high performance routes in the modified design also provided time and fuel benefits to the user. Consequently, from a sample of one terminal area flow, the modified design approach appears to be superior to the strict application of the RNAV Task Force terminal design approach. In order to validate this hypothesis a series of briefings were presented to field controllers at the selected terminal areas and a second terminal route design task was performed.

7.5.1 Recommended RNAV Terminal Area Design Procedures

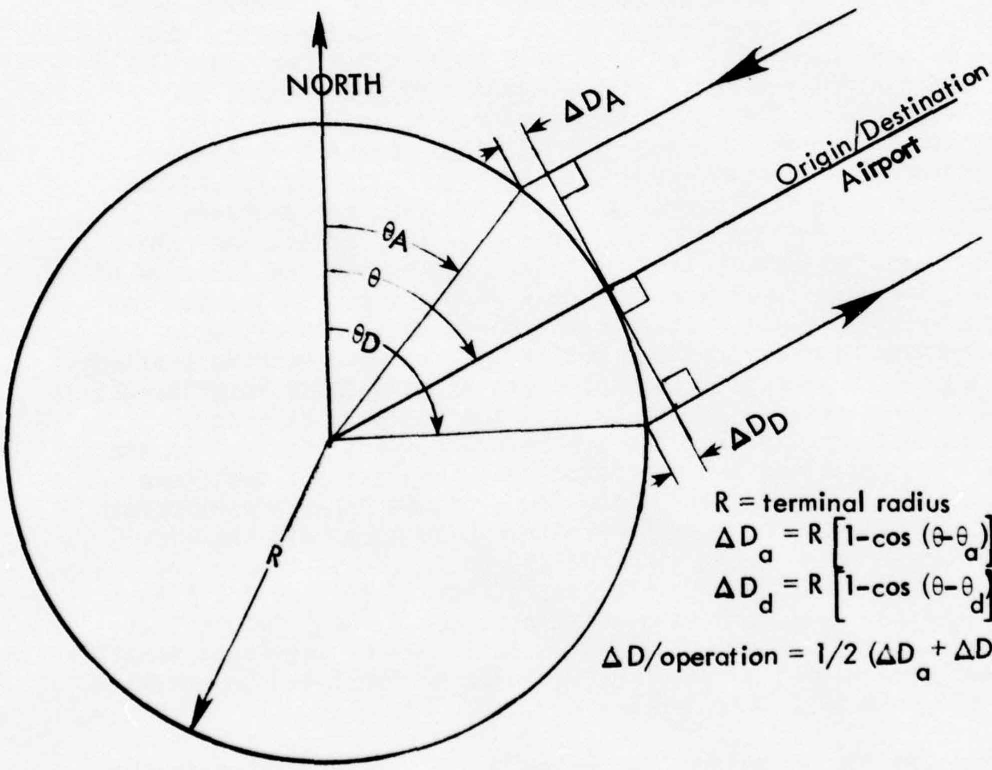
7.5.1.1 Field Controller Inputs

During the briefings that were given at the FAA Regions, comments were obtained from the controllers concerning the types of characteristics that they would desire to see in an RNAV terminal area route structure. In all of the briefings the controllers rejected the concept of a standardized terminal area configuration. They indicated that each terminal area had unique characteristics which would affect the terminal area ATC operations. The only way to efficiently account for these characteristics is to pattern the terminal route structure in a manner so as to minimize the problems associated with operations in that specific area. In particular, the controllers mentioned that the enroute traffic flows, the number and location of airports, and the runway configurations at these airports all influenced the selection of terminal area routes. Other constraints which are often imposed upon the terminal route locations are noise problems, terrain problems, populated areas, etc. One specific comment concerning waypoint location was voiced by several controllers. The concept of a low altitude departure waypoint seemed to the controllers to produce an unnecessary "dogleg" in the departure route. This point was substantiated by an analysis of departure route lengths with and without including the low altitude departure waypoint in the route. A more desirable departure technique is to permit the aircraft to climb to a safe maneuvering altitude and then turn it toward the high altitude departure waypoint where the aircraft would be handed off to the appropriate Air Route Traffic Control Center sector. The comments that were received from the controllers were used as an input for the final terminal area design and for determining a set of recommended terminal design guidelines for use in the post-1982 RNAV designs.

The recommended design procedures described below, and reflected in the recommended terminal area design guidelines given in Section 8, were developed to provide specific techniques which will produce user benefits. It should be noted that the application of these techniques must be tempered by consideration of individual terminal area characteristics and the resulting design may be modified somewhat by the enroute structure interface. Terminal area designs should be developed in concert with the adjacent enroute structure to create a master route structure plan. The master plan development should rely on the available analysis techniques to insure optimization of user benefits, but should also include a simplified methodology which can be readily applied by field personnel as the need arises.

7.5.1.2 Analytical Design Procedures

The modified terminal area design guidelines describe the desirable attributes of a terminal area route structure in general terms. The initial task in the modified design effort was directed toward determining some quantitative measure of the alignment of the terminal area boundary waypoints with the enroute traffic flow. The measure that was selected is the excess distance traveled by an aircraft due to the fact the waypoint that is used for arrival or departure is not precisely aligned with the direction of the origin or destination airport. An example of this measure for a single aircraft is shown in Figure 7.57. The origin or destination airport for this aircraft is located at a bearing θ from the true north as measured from the center of the terminal area. The arrival waypoint that will be used by the aircraft is located at a bearing of θ_A from true north and the corresponding departure waypoint bearing is θ_D. The excess distance flown by the arriving



R = terminal radius

$$\Delta D_a = R\left[1-\cos(\theta-\theta_a)\right]$$

$$\Delta D_d = R\left[1-\cos(\theta-\theta_d)\right]$$

$$\Delta D/\text{operation} = 1/2\,(\Delta D_a + \Delta D_d) \quad \text{(Equation 7.1)}$$

Figure 7.57 Alignment of Terminal Waypoints

aircraft is shown as ΔD_A in Figure 7.57. The corresponding excess distance for the departure is ΔD_D. Assuming that for each arrival from the origin city there is also a departure to that city, the net ΔD/operation is given by Equation 7.1. In order to apply this measure of design effectiveness to all aircraft using the specified terminal area, a traffic weighted measure of ΔD/operation was used. This expression is given by Equation 7.2.

$$\Delta D/\text{operation} = \frac{1}{N_T} \sum_{i=1}^{K} \left[n_i\,(\Delta D_{Ai}) + m_i\,(\Delta D_{Di}) \right] \qquad \text{(Equation 7.2)}$$

where

N_T = total number of terminal operations

$$N_T = \sum_{i=1}^{K} (n_i + m_i)$$

n_i = number of arrivals from airport i

m_i = number of departures from airport i

K = number of airports

ΔD_{Ai} = excess arrival distance for airport i

ΔD_{Di} = excess departure distance for airport i

In order to minimize the ΔD/operation for a specified terminal area, an optimization technique was applied using Equation 7.2 as the measure to be minimized. The problem was begun by dividing the terminal airspace into an even number of sectors (alternating arrival and departure sectors) and specifying the number of waypoints to be used per sector. The waypoints were uniformly spaced on the boundary of each sector. The initial alignment of the sectors with respect to true north was an arbitrary input parameter to the program. The terminal area radius was also specified as an input parameter. The terminal waypoints were not permitted to be any closer than eight (8) miles apart on the terminal boundary. This distance was based on a $\pm$ 4 nm enroute route width.

To begin the optimization process, each sector boundary was moved first clockwise and then counter clockwise a specified number of degrees. At each sector boundary setting, the waypoints in the adjacent sectors were redistributed uniformly on the perimeter of the sector. At each of these sector boundary settings, the traffic was distributed in such a manner as to use the closest arrival or departure waypoint. The ΔD/operation was computed at each sector setting. Then that sector boundary was set at the bearing which minimized the ΔD/operation parameter. Then the next sector boundary was moved and so on around the terminal area until all of the sector boundaries have been set to minimize the ΔD/operation for the specified step size. Then the step size was halved and the procedure was restarted. When the step size dropped below a preset value (usually 1°) the process was terminated and the ΔD/operation and the corresponding waypoint locations were recorded.

It was found during the computations that several local minima existed. Consequently, the initial orientation of the sectors was changed through a series of uniform steps in order to establish an overall minimum.

Several combinations of number of sectors and waypoints per sector were used to investigate several candidate terminal area configurations. Some of the most common combinations were 8 sectors with 3 waypoints per sector and 10 sectors with 2 waypoints per sector.

In order to effectively utilize the terminal area waypoint location program, it was necessary that comprehensive traffic samples be available for each of the airports under consideration. The source of data that was selected to provide this data was the December, 1974 Official Airline Guide [15]. Only high altitude jet traffic was included in the traffic sample. Although this document does not contain information on general aviation and non-scheduled airline operations, it does represent an accurate estimate of the relative level of aircraft traffic flow between the listed cities.

The route structures in the terminal maneuvering area were designed to provide a minimum path length from the runway in use to the terminal area waypoint that was established by the optimization program. Considerations were given to crossing traffic situations and modification of the minimum distance consideration was used as required. Arrival aircraft approached the airport in the conventional downwind, base and final-approach type of flight path. Where appropriate, baseleg entries and straight-in approaches were used. It may be noted that the minimization of ΔD/operation leaves open the question as to which sectors should be used for arrivals and which sectors should be used for departures. An analysis of equation 7.2 indicates that this choice of sectors is completely arbitrary as long as the sectors are alternate arrival and departure areas. Consequently, the choice of arrival and departure sectors was based on the alignment which most closely resembled present day traffic alignment. This technique should aid in the implementation of RNAV routes from the post-1982 design into the present terminal area route structure during the transition phase, thereby allowing early realization of user benefits.

Altitude determination in the modified design was accomplished through the use of the vertical envelope concept which is described in Section 7.4.2. This concept allows pilot selection of 3D gradients within the envelope. Separation required for 3D gradients up to 6° was provided by the location of 2D altitude restriction points, as discussed in Appendix A. One minor modification to these vertical profiles was necessary at Denver due to the 5,000 ft altitude of the airport. This modification provided a means to account for the reduced climb performance for aircraft at these altitudes.

The waypoints in the terminal maneuvering area were generally located in a manner to provide for the standard downwind, base and final approach segments. The field controllers that were contacted during the briefings at the regions suggested that they would like to see a more gradual intercept angle between the base leg and the final approach leg in the terminal maneuvering area. However, it was decided that the routes shown on the maps should depict the waypoint locations rather than the flight path of the aircraft. Consequently, the 90° turn from base to final was retained in the final post-1982 designs.

7.5.2 Post-1982 Final Design Applications

7.5.2.1 Final Post-1982 New Orleans Design

The final post-1982 New Orleans terminal area designs are shown in Figures 7.58 and 7.59. Terminal waypoints were selected by the optimum waypoint location program which was described in a previous section. The traffic sample that was used to develop these waypoint locations is shown in Table 7.9.

Six different cases of sectors and waypoints were considered. These cases (number of sectors/total number of waypoints) and their associated value of ΔD/operation are shown in Table 7.10. The three cases that are labeled E.S. are cases in which the sectors were constrained to be of equal size. For instance, the 8/24 E.S. case has eight 45° sectors while the 10/20 E.S. case and the 10/30 E.S. case has 36° sectors. It is apparent from the data shown in Table 7.10 that the equal segment constraint produces poorer ΔD/operation values compared to the unconstrained sector size cases. It was determined that 30 waypoints around the periphery of New Orleans terminal area were more than necessary to accommodate the traffic for this medium density terminal area. The 10/20 case produced optimum routes that also resulted in very good agreement with current arrival and departure areas. Consequently, this configuration was chosen as the basis for completing the design. After the design was completed, the value of Δ D/operation was computed from the actual location of the terminal waypoints as recovered from the chart. In addition, the ΔD/operation was computed for the 1972 RNAV route structure described in Section 4.1.1.4. These values are shown in Table 7.11. It is quite apparent that the 1982 RNAV route structure produces a considerable improvement over the 1972 route structure.

Table 7.10 Waypoint Optimization Results for New Orleans

Sectors/Waypoints	ΔD /Operation
8/24	0.60 nm/Operation
10/20	0.68
10/30	0.43
8/24 E.S.	1.10
10/20 E.S.	0.94
10/30 E.S.	0.62

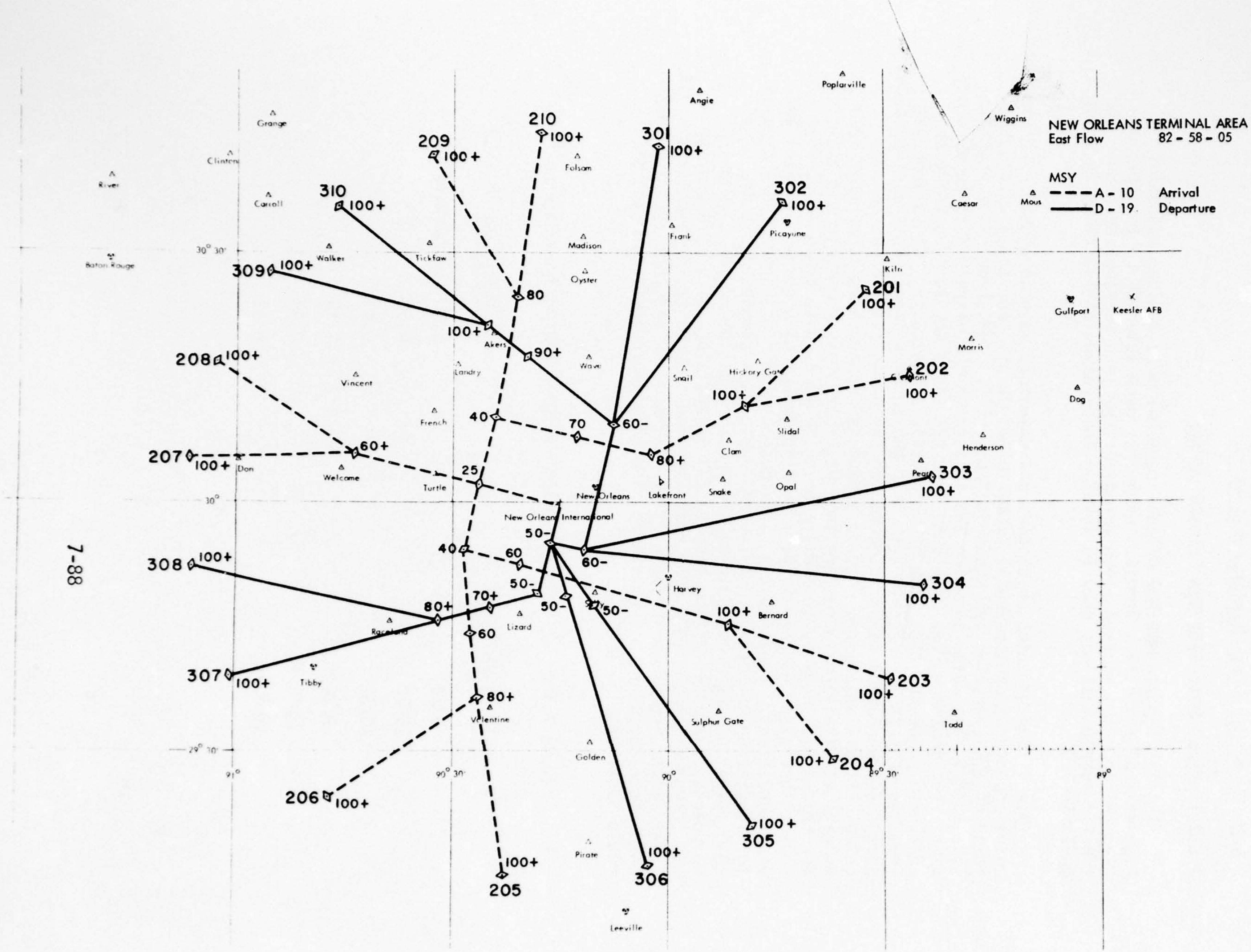


Figure 7.58 New Orleans Terminal Area - Final Post-1982 RNAV Design, East Flow

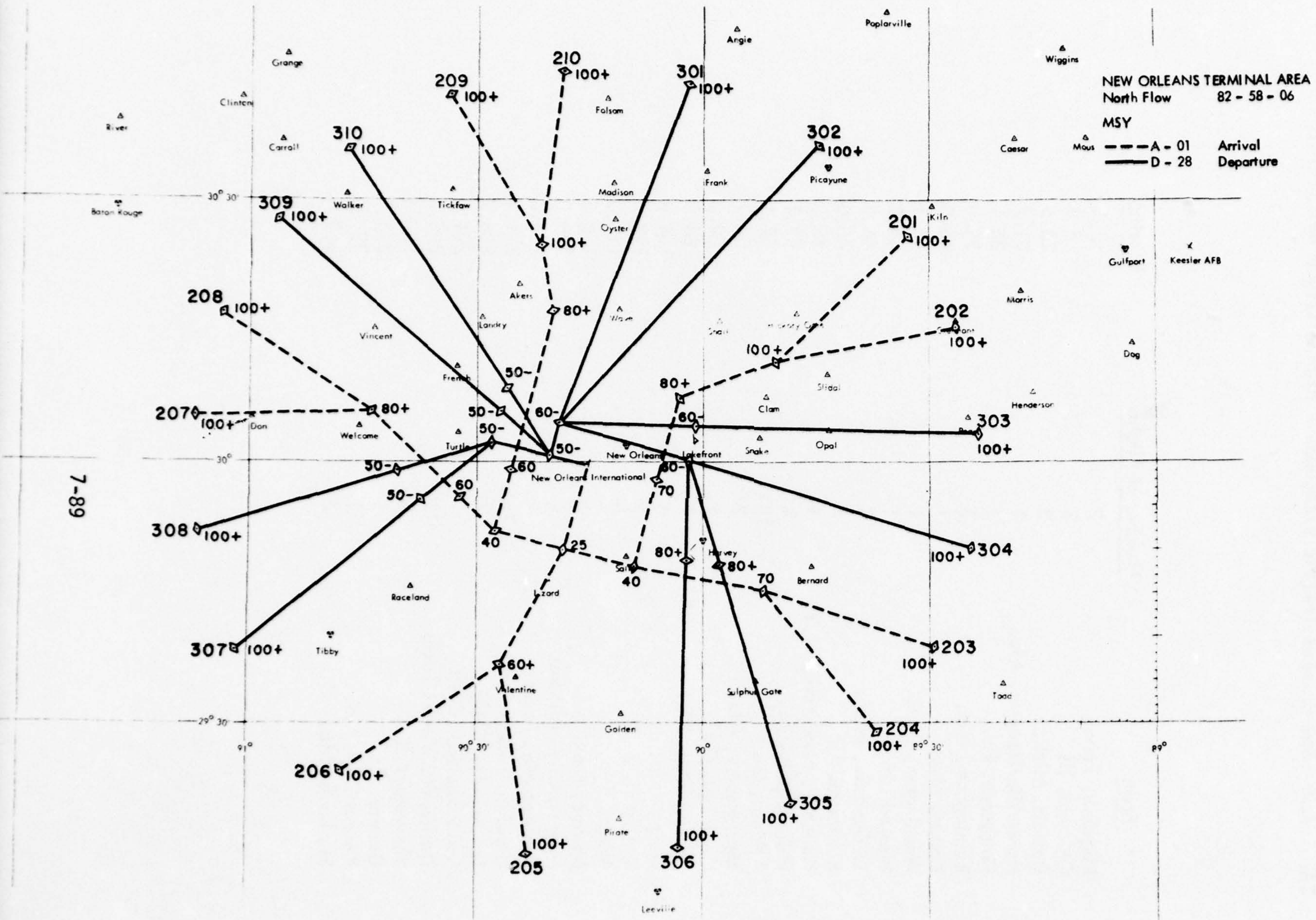


Figure 7.59 New Orleans Terminal Area - Final Post-1982 RNAV Design, North Flow

TABLE 7.9 New Orleans Traffic Exchanges - High Altitude Jet Traffic

From	Number of Flights	Bearing
Memphis, Tenn.	7	2.5
Chicago, Ill.	3	8.3
Detroit, Mich.	3	22.5
Huntsville/Decatur, Ala.	1	31.7
Pittsburgh, Pa.	2	35.1
Birmingham, Ala.	3	38.8
Boston, Mass.	1	46.0
Washington, D. C.	1	46.1
Newark, N.J.	1	46.3
La Guardia, N.Y.	1	46.5
Baltimore, Md.	2	46.8
Kennedy, New York, N.Y.	4	47.0
Philadelphia, Pa.	2	47.1
Atlanta, Ga.	13	52.1
Montgomery, Ala.	2	54.1
Columbus, Ga.	1	59.5
Jacksonville, Fla.	1	84.0
Tampa, Fla.	4	104.7
San Jaun, P. R.	2	112.6
Miami, Fla.	7	113.0
Merida, Mexico	1	176.5
Mexico City, Mexico	1	219.0
San Antonio, Texas	1	268.3
Houston, Texas	18	271.1
Los Angeles, Calif.	2	286.7
San Francisco, Calif.	1	294.6
Dallas/Ft. Worth, Texas	12	298.3
Shreveport, La.	3	309.6
Denver, Co.	1	313.1
Kansas City, Mo.	1	339.6
St. Louis, Mo.	2	359.4

Table 7.11 Excess Distance Comparison for New Orleans

MSY Configuration	ΔD/Operation
1972 RNAV East	1.36 nm/Operation
1972 RNAV North	1.82
1982 RNAV East	0.73
1982 RNAV North	0.73

The designs as depicted in Figure 7.58 and 7.59 show generally close agreement with the arrival and departure areas that are in use currently at New Orleans. The 1972 arrival/departure areas and the corresponding post-1982 routes are as follows:

Optimum Post-1982 Arrival Routes	Relationship to 1972 Arrival Areas
201-202	Slightly north of Slidell intersection
203-204	Slightly south of Bernard intersection
205-206	About 15 miles west of Golden intersection
207-208	Overlie Welcome and Vincent intersections
209-210	Slightly west of Oyster intersection

Optimum Post-1982 Departure Routes	Relationship to 1972 Departure Areas
301-302	Slightly west of Frank & Hickory intersections
303-304	Close to Snake departure area
305-306	Slightly west of Sulphur Gate intersection
307-308	Overlie Tibby departure area
309-310	Overlie Walker and Albany departure areas

The terminal maneuvering area routes were constructed with relatively little difficulty insofar as crossing route conflicts or altitude restriction problems are concerned. The correspondence between the optimum post-1982 RNAV routes and the 1972 New Orleans VOR/radar vector routes is sufficiently close so as to permit several routes to be implemented as soon as there is a user requirement for these terminal RNAV routes.

Each of the arrival routes are shown with a feeder fix located approximately 25 nm from the airport. This point corresponds to the low altitude arrival waypoint in the initial 1982 designs. This point may be used for a handoff point between center and approach control. If this point is not necessary from an operational standpoint it is possible to provide more direct routes for arrivals by removing the "doglegs" that result from using the low altitude arrival waypoint.

7.5.2.2 Final Post-1982 Denver Designs

The final post-1982 Denver terminal area designs are shown in Figures 7.60 and 7.61. Terminal area waypoints were selected with the assistance of the optimum waypoint location program and a comprehensive traffic sample. The traffic sample is shown in Table 7.12. Several different cases of terminal area sectors and waypoints were considered. The cases and their corresponding values of excess distance (ΔD/Operation) are shown in Table 7.13.

Table 7.13 Waypoint Optimization Results for Denver

Sectors/Waypoints	D/Operation
8/24	0.94
10/20	0.88
10/30	0.68
8/24 E.S.	1.25
10/20 E.S.	1.20
10/30 E.S.	0.85

The 10 sector, 20 waypoint configuration resulted in an excess distance value of only 0.20 nm/operation (from 0.68 to 0.88) more than the optimum 30 waypoint case. The 10 sector/20 waypoint configuration was selected as the basis for completing the design, since it corresponded generally with existing flows and would minimize implementation problems in the transition phase and provide for early user benefits.

RNAV terminal area routes were then developed for Denver. Designs were developed for the preferred west flow configuration and for the operationally difficult east flow configuration. Upon completion of the designs the excess distance was computed for both the 1972-1977 RNAV route structures, which overlie the Denver VOR/radar vector routes, and the post-1982 RNAV routes, which were based on the optimum waypoint location analysis. The results of this analysis is shown in Table 7.14. It can be seen that a considerable improvement in reducing excess distance was achieved. The slight difference between the theoretical excess distance value of 0.88 nm/operation from the analysis program and the value of 0.98 nm/operation which was determined from the actual design occurs due to the fact that some slight movement in waypoint location is introduced in the design process. These differences are small and are not significant when compared with the overall improvment in the excess distance value between the 1972-1977 and post-1982 configurations.

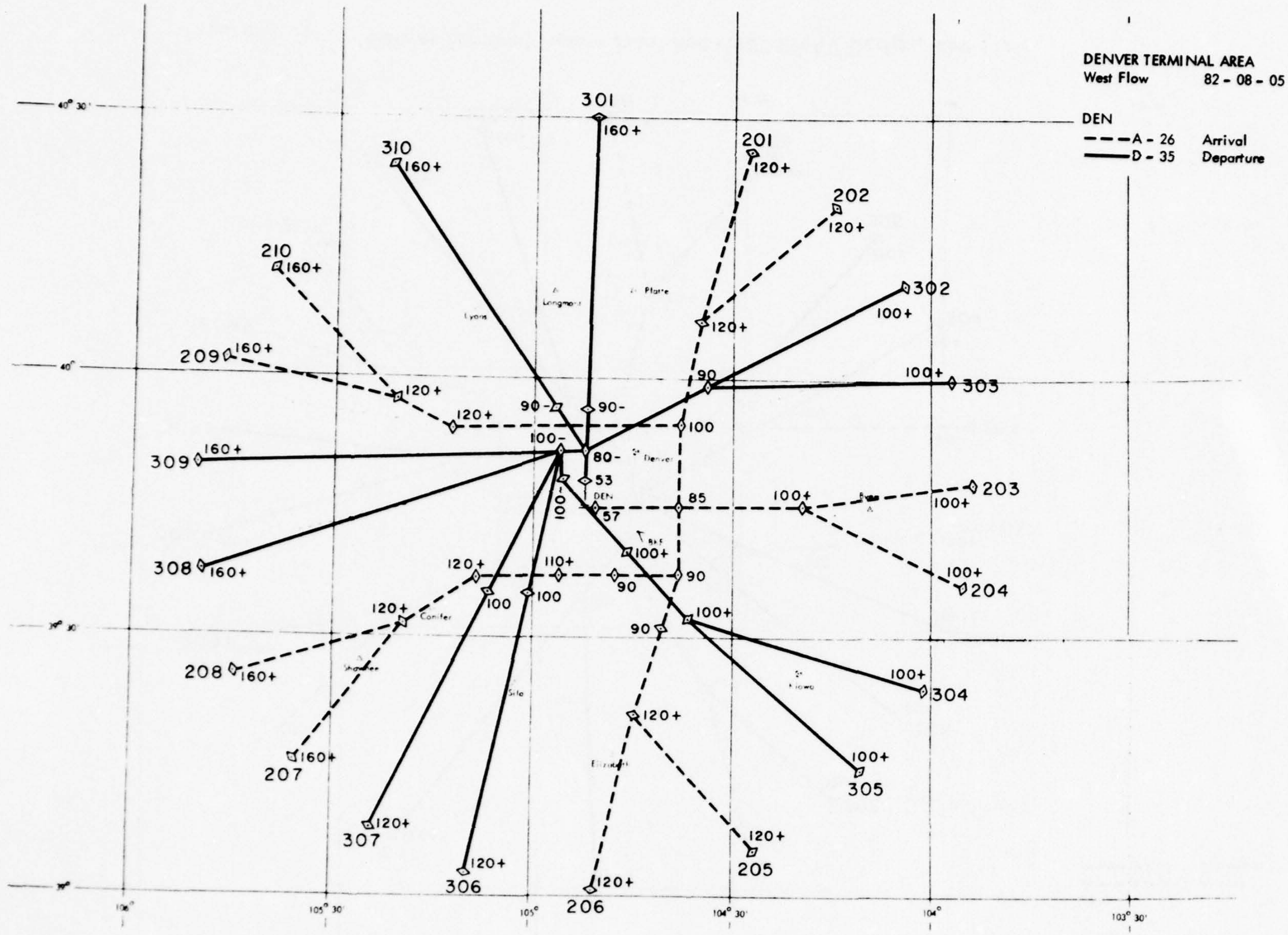


Figure 7.60 Denver Terminal Area – Final Post-1982 RNAV Design, West Flow

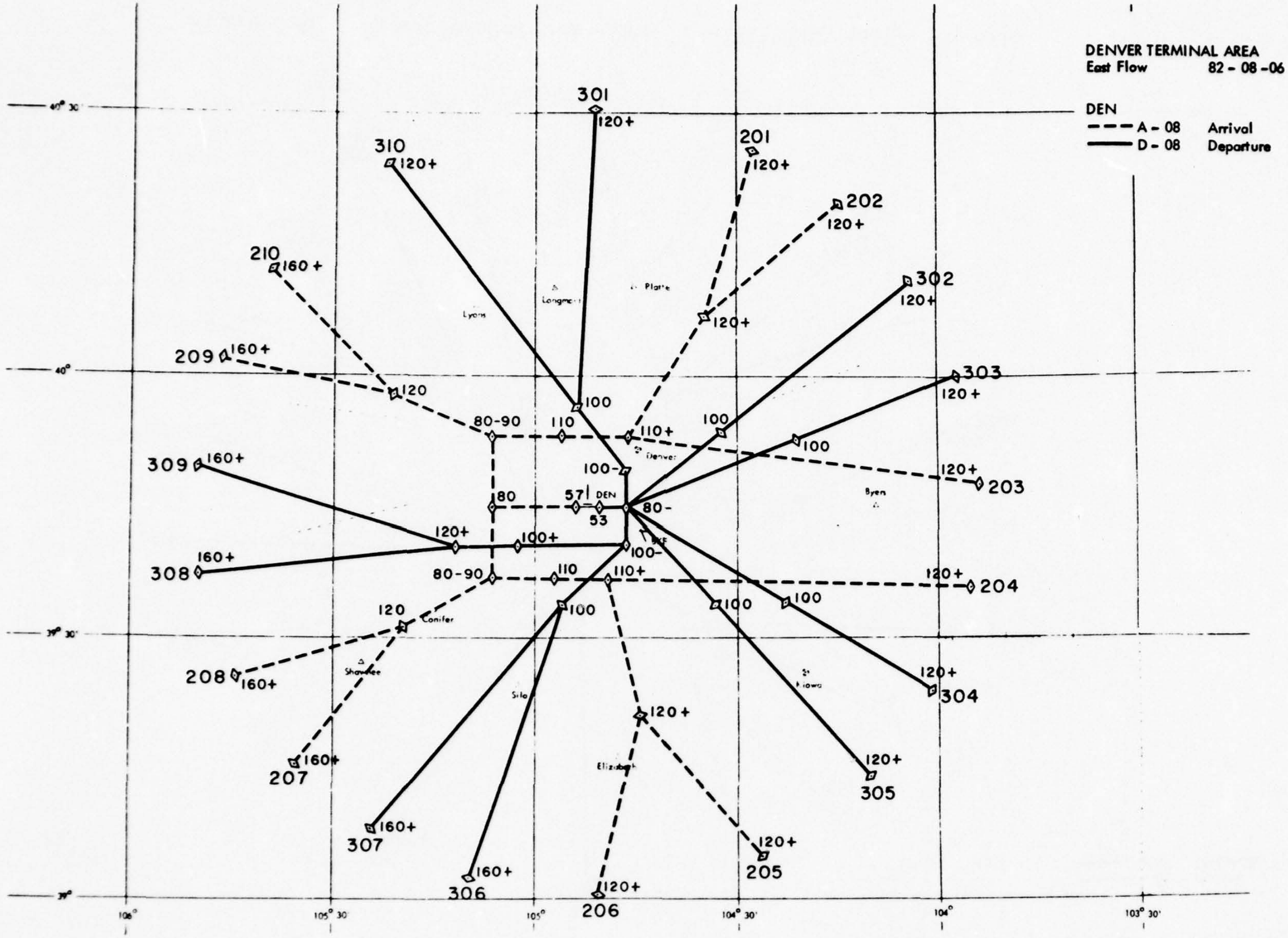


Figure 7.61 Denver Terminal Area - Final Post-1982 RNAV Design, East Flow

Table 7.12 Denver Traffic Exchanges-High Altitude Jet Traffic

From	Number of Flights	Bearing	From	Number of Flights	Bearing
Minot, N.D.	1	15.6	Dallas/Ft.Worth, Texas	16	135.0
Rapid City, S.D.	4	16.9	Houston, Texas	4	138.5
Bismark, N.D.	1	21.7	Amarillo, Texas	2	150.0
Sioux Falls, S.D.	2	55.2	San Antonio, Texas	2	150.8
Minneapolis, Minn.	8	55.4	Midland, Texas	1	163.7
Sioux City, Iowa	3	64.3	Mazatlan, Mexico	1	185.2
Milwaukee, Wis.	3	70.4	Taos, New Mexico	1	190.9
Boston, Mass.	3	72.0	Santa Fe, New Mexico	1	193.3
Cedar Rapids, Iowa	1	73.7	Albuquerque, New Mexico	7	196.6
Detroit, Mich	2	74.4	Durango, Co.	2	221.6
Omaha, Neb.	8	74.4	Phoenix, Ariz.	11	224.3
Des Moines, Iowa	3	74.6	San Diego, Calif.	3	238.4
Chicago, Ill.	15	74.6	Ontario, Ca.	2	244.6
Moline, Ill.	1	76.5	Los Angeles, Calif.	11	245.9
Cleveland, Ohio	2	77.1	Las Vegas, Nev.	9	248.7
Lincoln, Neb.	3	77.4	Grand Junction, Co.	3	258.2
Newark, N.J.	2	77.7	Fresno, Calif.	1	260.2
New York, N.Y.	4	77.7	San Jose, Calif.	2	265.1
Pittsburgh, Pa.	1	79.8	San Francisco, Calif.	8	266.6
Philadelphia, Pa.	1	80.1	Oakland, Calif.	1	266.9
Baltimore, Md.	1	82.4	Sacramento, Calif.	2	270.6
Washington, D.C.	3	83.3	Reno, Nev.	2	273.4
Kansas City, No.	11	90.1	Salt Lake City, Utah	14	282.9
St. Louis, Mo.	8	90.5	Boise, Idaho	2	297.8
Memphis, Tenn.	1	107.0	Portland, Ore.	6	299.9
Wichita, Kan.	5	107.6	Seattle, Wash.	7	307.1
Tulsa, Okla.	1	113.9	Jackson, Wyo.	1	313.2
Garden City, Ka.	2	118.2	Spokane, Wash.	2	314.2
New Orleans, La.	1	124.7	Calgary, Alta.	2	333.5
Oklahoma City, Okla.	4	124.8	Billings, Mont.	1	337.2
Liberal, Ka.	2	130.3	Casper, Wyo.	3	339.7

Table 7.14 Excess Distance Comparison for Denver

Configuration	ΔD/Operation
1972 RNAV East	2.21
1972 RNAV West	2.21
1982 RNAV East	0.98
1982 RNAV West	0.98

In general there exists a very close correspondence between the 1972-1977 RNAV routes and the post-1982 optimized Denver route structure. However, one major area of change is in the region north and northwest of the airport. In this area the arrival routes over Lyons, Longmont and Platte intersections were essentially split into two parts. One part was moved to the east and one part was moved to the west. In between this split, two departure routes were developed. The correspondence between the post-1982 routes and the existing arrival/departure areas is shown in the following list:

Post-1982 Arrival Routes	1972 Arrival Fixes
201-202	Moved east from Lyons, Longmont, Platte
203-204	Overlies Byers intersection
205-206	Overlies Elizabeth intersection
207-208	Overlies Shawnee intersection
209-210	Moved west from Lyons, Longmont, Platte

Post-1982 Departure Routes	1972 Departure Fixes
302-303	Overlies Roggen departure area
304-305	Overlies Pueblo departure area
306-307	Overlies Silo departure area
308-309	Overlies Golden and Superior departure areas
310-301	New departure area

No major problems were encountered in developing the terminal maneuvering area routes for the west flow at Denver. The one potential problem area lies in the paths of routes 304 and 305 to the southeast. Aircraft on these routes are required to climb to 10,000 ft or above before they cross the south downwind leg. In general this altitude should be no problem for most jet aircraft using these routes. Also, no major problems should be encountered for aircraft using the east flow at Denver with one possible exception. Routes 308 and 309 departing west over the mountains must be at sufficient altitude 10-20 miles west of the airport to provide obstruction clearance for this fast rising terrain.

Because of this restriction it was considered desirable for these departures to top the arrivals in this area. This places a minimum altitude constraint of 10,000 ft upon these aircraft before they cross the base leg for the arrival traffic. Several trial designs were attempted in this area including taking these departures either north or south of the downwind leg before turning them west. This produced a conflict, however, with the arrivals from routes 207-208 and 209-210. This conflict was made particularly acute due to the shallow intersection angle at the points where the routes crossed. The final location of routes 308 and 309 which is shown in Figure 7.61 was selected because it presented a problem only to those aircraft which have poor climb capabilities. For these aircraft additional altitude can be obtained by extending the eastbound portion of the departure for a specified distance which will extend the flight path thus giving the aircraft more time to climb.

A low altitude arrival waypoint was provided on each arrival route at a distance of 25 miles from the airport. If this waypoint is not required for operational reasons such as a handoff point, then these arrival routes could be straightened, thus providing a slightly shorter route for the arrivals.

7.5.2.3 Final Post-1982 Philadelphia Design

The final post-1982 Philadelphia terminal area designs are shown in Figures 7.62 and 7.63. The waypoints on the 45 nm boundary of the terminal area were determined by the optimum waypoint location program. The traffic sample that was used to determine these waypoint locations is shown in Table 7.15. Several combinations of terminal area sectors and number of waypoints were considered. A list of these several cases is shown in Table 7.16. As in the case of New Orleans and Denver, the 10 sector/20 waypoint configuration was chosen as a basis for completing the post-1982 RNAV route structure at Philadelphia. It can be observed that all of the configurations that are listed in Table 7.17 produced relatively small excess distance values. Consequently, the major consideration in selecting the final waypoint location was the relative alignment of the post-1982 routes as compared to currently used arrival and departure areas, in order to minimize implementation problems in the transition phase and provide for early user benefits. The 10 sector/30 waypoint configuration was rejected due to the large number of routes that such a design would produce. These many routes would actually create less efficiency in the Philadelphia operation due to the reduced flexibility that is available to the controller in handling traffic on these routes (i.e., little room for "parallel offsets" or "direct to" requests to handle tactical situations).

The RNAV terminal area route structure was then developed for both the west flow and east flow at Philadelphia. No major problem areas were encountered in developing either of the Philadelphia designs. The only potential problem areas with the east flow configuration are minimum crossing altitude requirements on several of the departure routes. Routes 306 and 307 must tunnel under the south downwind at an altitude of 5000 ft or below and once clear of this route they must climb to top arrival routes 205 and 206 at 7000 ft or above. This procedure should produce little difficulty for most of the jet aircraft that use the Philadelphia area. Routes 308 and 309 must make a 180° climbing left turn and top 6000 ft before they cross the base leg for the north

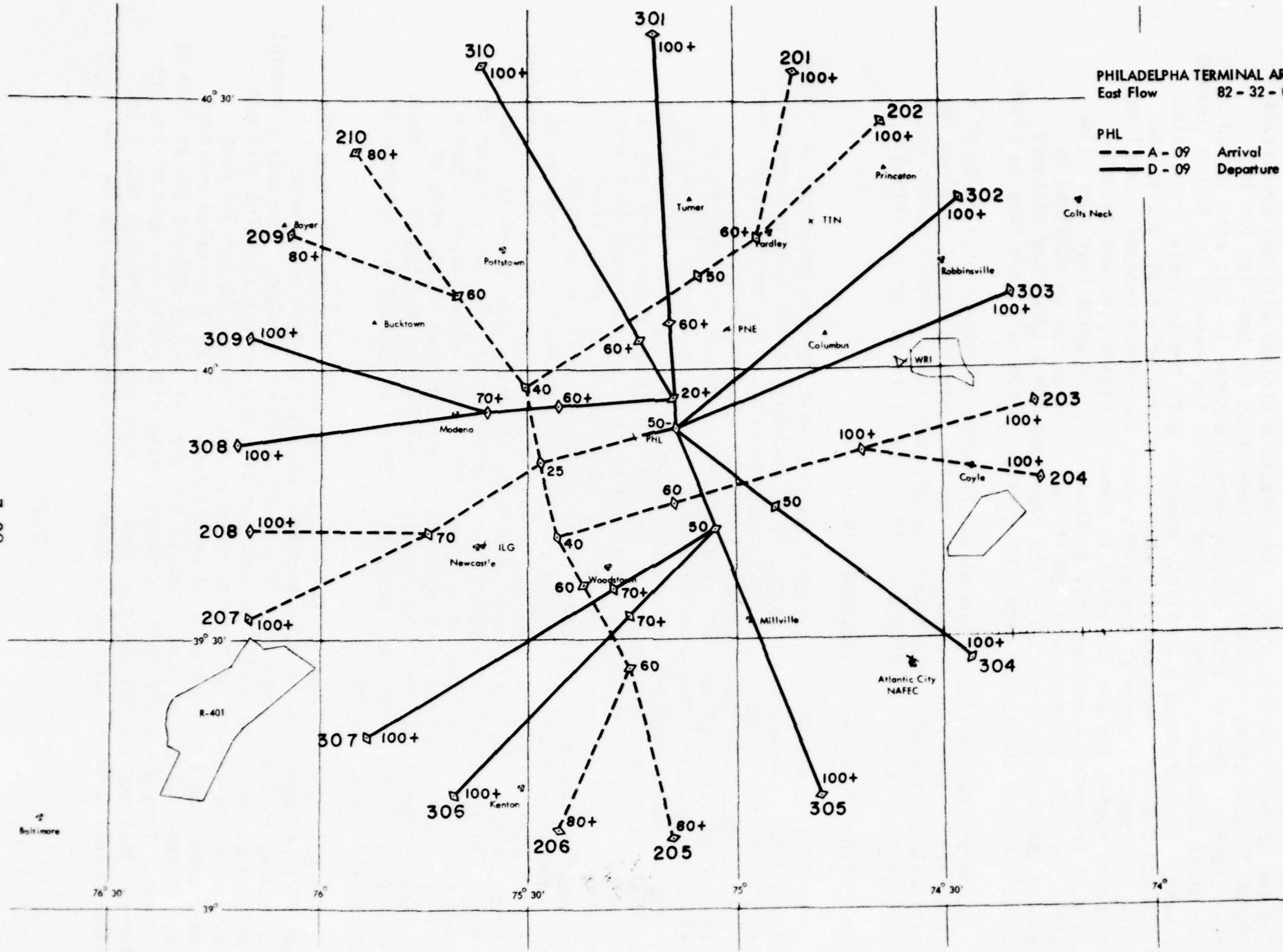


Figure 7.62 Philadelphia Terminal Area-Final Post-1982 RNAV Design, East Flow

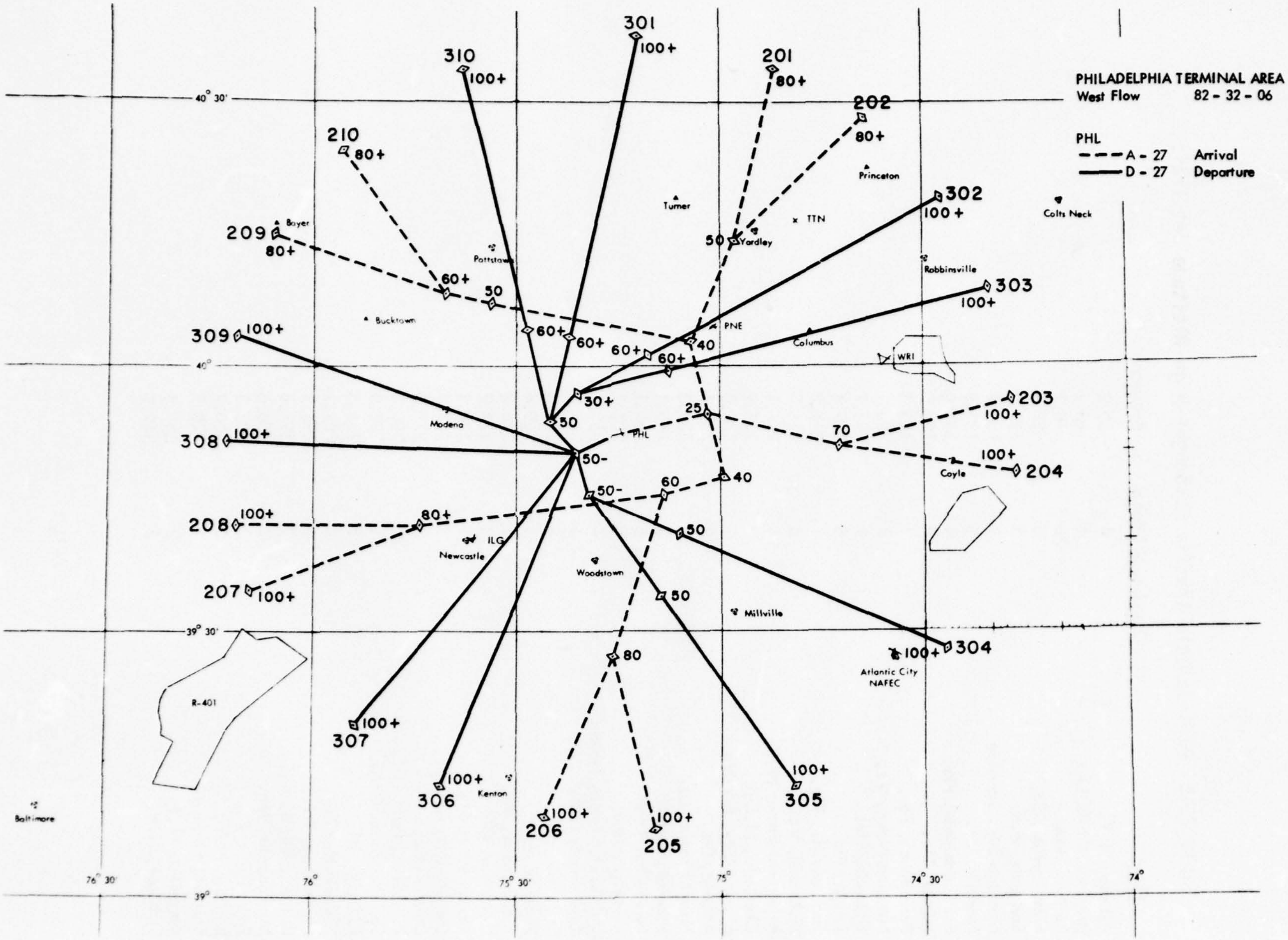


Figure 7.63 Philadelphia Terminal Area-Final Post-1982 RNAV Design, West Flow

Table 7.15 Philadelphia Traffic Exchanges-High Altitude Jet Traffic

From	Number of Flights	Bearing
Albany, N.Y.	4	20.2
Hartford, Ct (BDL)	5	45.7
Boston, Mass.	25	50.7
New London, Ct.	3	57.9
San Juan, P.R.	3	157.3
Montego Bay, Jamaica	1	186.9
Norfolk, Va.	5	194.5
Ft. Lauderdale, Fla.	4	198.0
Miami, Fla.	7	198.2
Palm Beach, Fla.	1	198.5
Newport News, Va.	2	200.1
Orlando, Fla.	2	205.7
Tampa, Fla.	5	209.1
Jacksonville, Fla.	1	211.2
Richmond, Va.	3	215.0
Raleigh/Durham, N.C.	1	216.1
Charlotte, N.C.	3	225.9
Mexico City, Mexico	1	232.0
Atlanta, Ga.	12	232.6
New Orleans, La.	2	235.8
Houston, Texas	1	245.1
Nashville, Tenn.	3	251.1
Memphis, Tenn.	1	252.2
Dallas/Ft. Worth, Texas	4	255.1
Cincinnati, Ohio	1	266.6
St. Louis, Mo.	3	269.3
Phoenix, Az.	1	269.4
Indianapolis, Ind.	1	272.6
Columbus, Ohio	3	273.7
Kansas City, Mo.	1	274.1
Los Angeles, Calif.	3	274.1
Denver, Co.	3	279.3
Pittsburgh, Pa.	21	280.8
San Francisco, Calif.	1	282.0
Chicago, Ill.	13	286.5
Cleveland, Ohio	8	289.1
Milwaukee, Wi.	1	292.1
Detroit, Metro, Mi.	7	293.6
Minneapolis, Mn.	2	296.6
Erie, Pa.	2	302.3
Buffalo, N.Y.	3	320.7
Toronto, Ontario	1	320.7
Rochester, N.Y.	2	331.5
Syracuse, N.Y.	2	349.1

Table 7.16 Waypoint Optimization Results for Philadelphia

Sectors/Waypoints	ΔD/Operation
8/24	0.67
10/20	0.81
10/30	0.59
8/24 E.S.*	0.92
10/20 E.S.	1.02
10/30 E.S.	0.79

* E. S. - Equal Sector Size Constraint Imposed

Table 7.17 Excess Distance Comparison for Philadelphia

Configuration	ΔD/Operation
1972 RNAV East	0.98
1972 RNAV West	0.96
1982 RNAV East	0.88
1982 RNAV West	0.88

arrivals. Similarly, aircraft on routes 310 and 301 must make a 90° left turn and climb to 6000 ft or above before they cross the north downwind leg. When these crossing altitudes were checked against the aircraft performance profiles, it was determined that most aircraft should have no difficulty in achieving these required minimum altitudes. In the west flow configuration, Figure 7.63, routes 310, 301, 302 and 303 must all make climbing right turns and achieve 6,000 ft before crossing the downwind leg for the north arrivals. Again, the climb performance profiles indicated that these altitudes are achievable for the aircraft that would be using the Philadelphia terminal area.

Due to several restricted areas in the Philadelphia area, several of the routes had to be moved slightly in order to avoid penetration of these areas by the routes. In particular routes 204 and 207 had to be moved several degrees from their optimum location as determined by the waypoint location analysis program.

After the designs had been completed, the excess distance (ΔD/operation) was computed for both the 1972 RNAV designs from Section 5.1.3.4 and the optimized 1982 designs. The results of this analysis are shown in Table 7.17. It was found that the optimized designs were slightly better from an excess distance standpoint, but the difference was considerably smaller than had been observed in several of the other terminal areas. From this analysis it is apparent that the existing Philadelphia route structure is quite well aligned with the Philadelphia traffic flow.

The correspondence between the 1972-1977 RNAV route structure from Section 5 and the post-1982 optimized route structure is relatively close. A list of the post-1982 routes and the corresponding 1972 arrival or departure areas is as follows:

Post-1982 Arrival Routes	1972 Arrivals Areas
201-202	Seven miles east of Turner intersection
203-204	Overlies Coyle arrivals
205-206	Slightly east of Kenton-Woodstown arrivals
207-208	Overlies New Castle arrivals
209-210	Slightly east of Bucktown arrivals

Post-1982 Departure Routes	1972 Departure Areas
302-303	Near Columbus, Robbinsville departures
304-305	Overlies Millville departures
306-307	Slightly west of Kenton departure
308-309	Overlies Modena departures
310-301	Slightly west of Pottstown departure

The design of the terminal maneuvering area routes at Philadelphia is generally based upon the procedures that are in use at the present time. An initial design effort attempted to bring the north downwind leg on both designs in closer to the airport in correspondence with a "box" pattern around the airport. This routes structure was discarded because it increased the distance flown by the north arrival traffic without providing any obvious benefit to the departures. If the northbound departures cannot achieve the 6000 ft minimum crossing altitude before crossing the north downwind leg, this procedure of moving the downwind leg closer to the airport and tunneling departures may have some merit. However, the procedures depicted on Figures 7.62 and 7.63 were retained in the 1982 optimized route structures at Philadelphia, and they conform generally to the current operation at Philadelphia.

The use of a low altitude arrival waypoint is shown on Figures 7.62 and 7.63 for use as a center/approach control handoff point. However, if there is no operational need for these waypoints then the arrival route could be shortened slightly by removing the necessity to overfly these waypoints and permitting the aircraft to approach the downwind or base leg directly.

7.5.2.4 Final Post-1982 Miami Design

The Mimai post-1982 RNAV terminal area designs which were based upon the optimum waypoint location program are shown in Figures 7.64 and 7.65. The traffic sample which was used to determine these waypoint locations is shown in Table 7.18. Several combinations of sectors and waypoints were analyzed for the Miami area before the design process was begun. A list of these combinations is shown in Table 7.19. It can seen that all of the combinations without the equal sector size constraint produced excess distance values of less than one mile per operation. Consequently, it was determined that any one of these configurations would produce a design that was satisfactory from the excess distance standpoint. When the waypoint locations, as determined by the optimum location program, were compared to the existing arrival

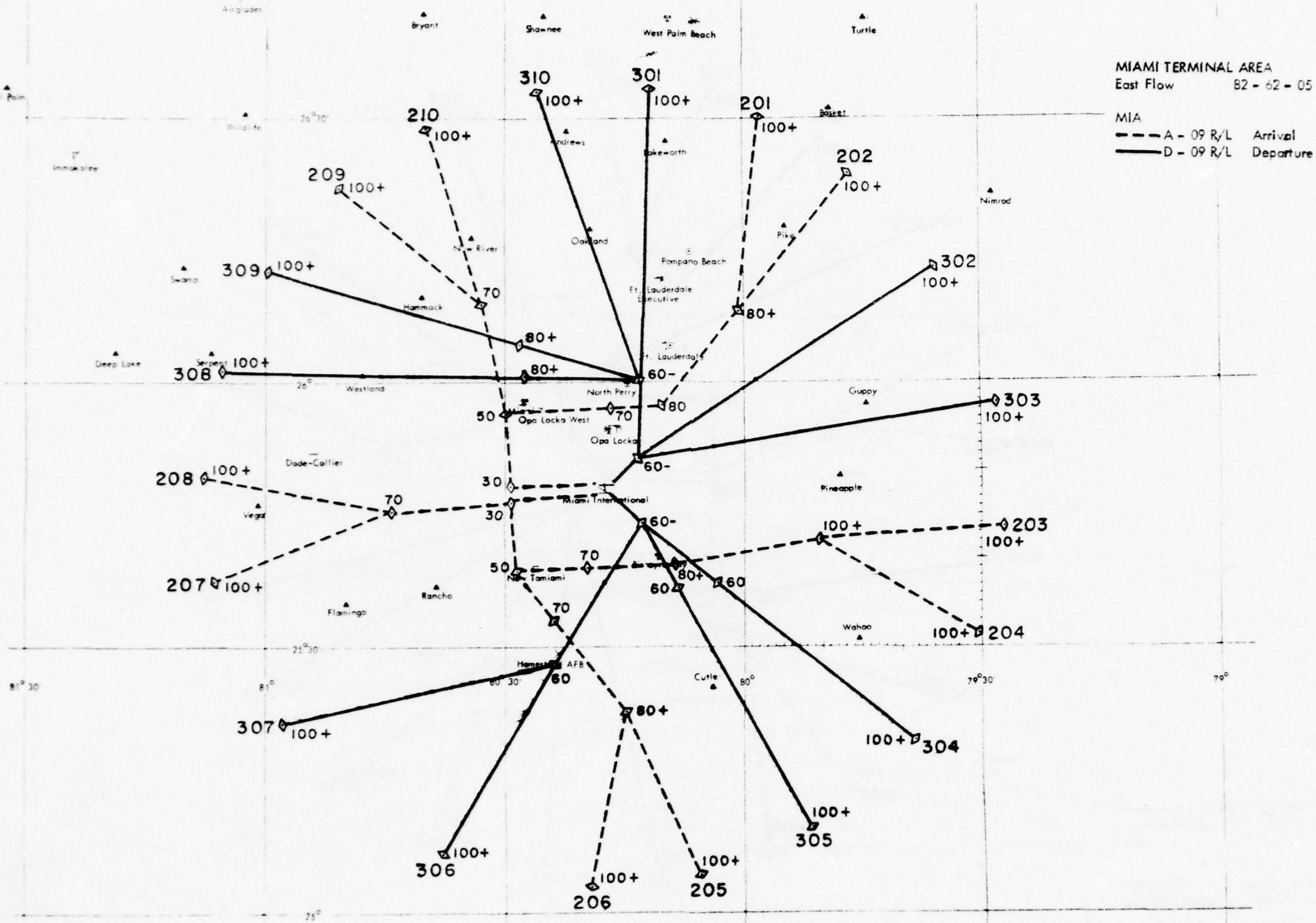


Figure 7.64 Miami Terminal Area - Final Post-1982 RNAV Design, East Flow

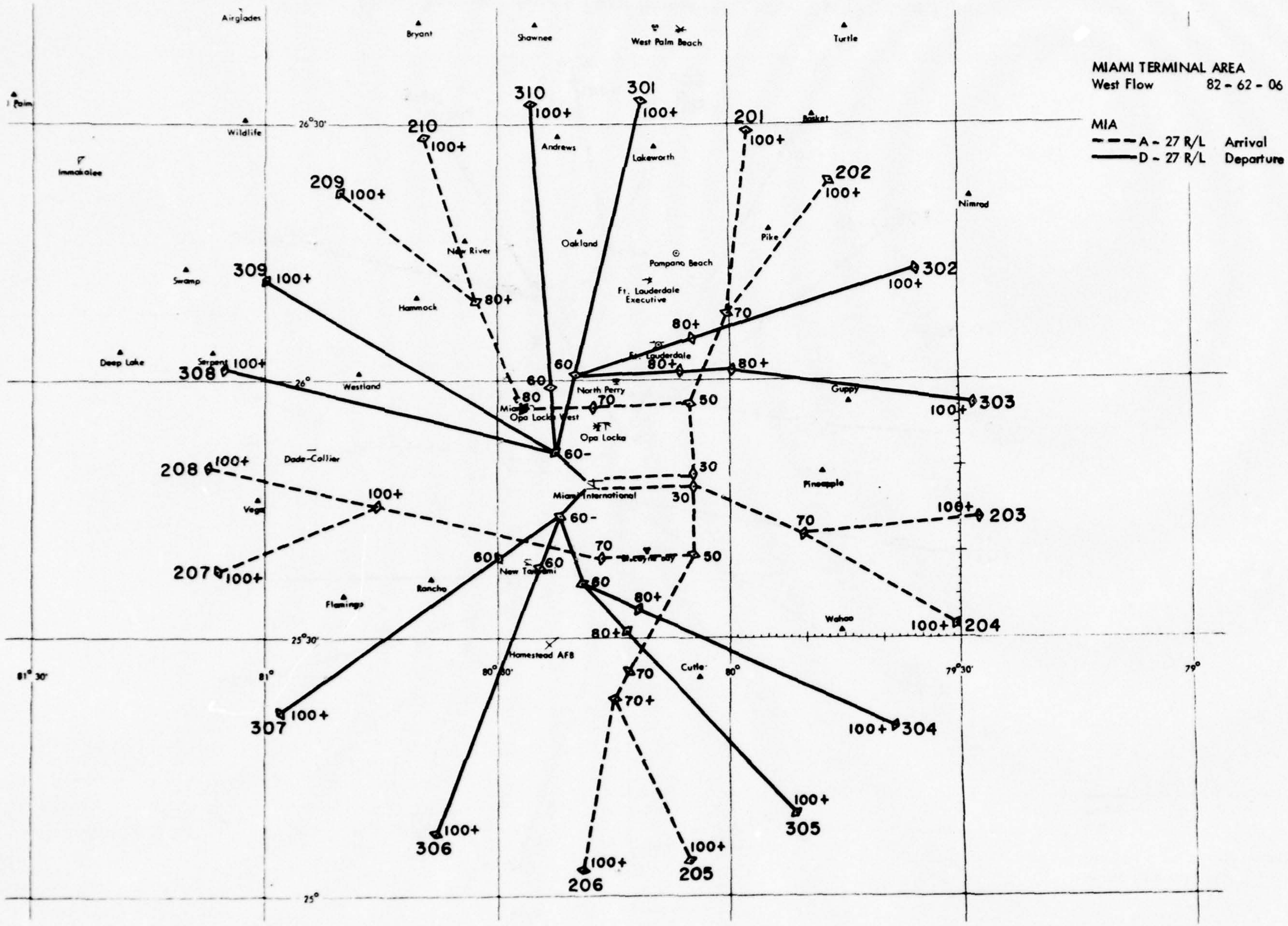


Figure 7.65 Miami Terminal Area-Final Post-1982 RNAV Design, West Flow

Table 7.18 Miami Traffic Exchanges-High Altitude Jet Traffic

From	Number of Flights	Bearing	From	Number of Flights	Bearing
Pittsburgh, Pa.	4	.2	Grand Cayman, W.Indies	3	188.0
Toronto, Ontario	2	1.5	San Jose, Costa Rica	2	194.3
Buffalo, N.Y.	1	3.9	Managua, Nicaragua	1	203.2
Rochester, N.Y	1	6.4	Guatemala City, Guatemala	2	222.5
Raleigh/Durham, N.C.	1	6.9	Belize City, Belize	2	223.5
Syracuse, N.Y	1	10.1	Cozumel, Mexico	1	230.5
Washington, D.C.	11	11.0	Merida, Mexico	1	242.5
Baltimore, Md.	2	11.9	Mexico City, Mexico	2	253.8
Montreal, Canada	2	13.5	Houston, Texas	6	290.9
Philadelphia, Pa.	7	15.4	Los Angeles, Calif.	3	293.1
Newark, N.J.	7	17.3	New Orleans, La.	7	297.8
La Guardia, N.Y.	10	18.0	San Francisco, Calif.	2	299.0
Kennedy, New York, N.Y.	17	18.4	Dallas/Ft. Worth, Texas	1	308.9
Hartford, Conn.	1	19.7	St. Peterburg, Fla.	1	315.3
Boston, Mass.	6	22.4	Tampa, Fla.	13	317.8
Providence, RI	1	22.4	Memphis, Tenn.	2	320.3
London, England	2	43.4	Birmingham, Ala.	1	325.7
St. Croix, Virgin Islands	1	116.2	St. Louis, Mo.	4	329.3
South Caicos, B.W.I.	1	116.2	Gainesville, Fla.	1	336.2
San Juan, P.R.	6	117.0	Atlanta, Ga.	18	336.4
Santo Domingo, Dom. Rep.	2	125.1	Orlando, Fla.	8	338.2
Port Au Prince, Haiti	2	132.0	Chicago, Ill.	9	340.7
Caracus, Venezuela	3	137.9	Louisville, Ky.	1	341.3
Brasila, Brazil	1	139.3	Indianapolis, Ind.	1	341.7
Rio de Janeiro, Brazil	1	140.3	Cincinnati, Ohio	2	345.6
Kingston, Jamaica	3	156.8	Jacksonville, Fla.	5	345.6
Barranquilla, Colombia	2	160.1	Daytona Beach, Fla.	1	348.8
Montego Bay, Jamaica	4	162.8	Columbus, Ohio	2	352.0
Bogata, Colombia	2	163.1	Detroit, Mich.	4	352.0
Cali, Colombia	1	170.1	Cleveland, Ohio	3	355.7
Lima, Peru	1	175.0	Charlotte, N.C.	1	356.8
Panama City, Panama	5	177.4			

Table 7.19 Waypoint Optimization Results for Miami

Sectors/Waypoints	ΔD/Operation
8/24	1.49
10/20	0.80
10/30	0.55
8/24 E.S.*	0.93
10/20 E. S.	1.08
10/30 E. S.	0.64

. * E. S. - Equal Sector Size Constraint Imposed

and departure areas, it was found that the ten sector case provided a reasonably close correspondence. In particular, the correspondence for the high density traffic areas to the north of the airport was virtually identical. As was the case at several of the other airports, the 30 waypoint configuration was rejected due to route congestion problems. Consequently, the 10 sector/20 waypoint configuration was chosen as a basis to begin the design procedure.

Since the boundary waypoints in the heavy traffic areas to the north were primarily located in the same areas as the existing routes, essentially the same procedures were used insofar as the organization of the terminal maneuvering area routes. Designs were developed for both the east flow and west flow for Miami. The only significant altitude restriction required for either flow occurs for traffic which is departing in a direction opposite that of the traffic flow. In Figure 7.64 for the east flow configuration, routes 308 and 309 are shown to tunnel under the downwind leg of the north arrival traffic and then make a left turn and climb to 8000 ft to cross arrivals from the New River area. Similarly, in Figure 7.65, for the west flow, traffic departing to the east and using the oceanic control areas again tunnel under the downwind leg of the New River arrivals and proceed to climb over the Pike area arrivals. The distance altitude profiles for several aircraft were checked and no problems should be encountered for most operational circumstances insofar as these minimum altitude restrictions are concerned.

Once the design was completed, a second excess distance computation was made which is based on the actual locations of the post-1982 routes. In addition, the excess distance value for the 1972 RNAV structure was computed. This comparison is shown in Table 7.20. It can be seen that approximately 0.6 nm can be saved through the use of the waypoint locations in the post-1982 designs.

A comparison was made of the location of the post-1982 RNAV routes and the currently used arrival and departure areas. Fairly close agreement is evident throughout the northern parts of the terminal area. However, to the south the correspondence is considerably less.

Table 7.20 Excess Distance Comparison for Miami

Configuration	ΔD/Comparison
1972 RNAV East	1.49
1972 RNAV West	1.49
1982 RNAV East	.87
1982 RNAV West	.87

Post-1982 Arrival Routes	1972 Arrival Areas
201-202	Overlies Pike arrivals
203-204	Eight nm north of Wahoo arrivals
205-206	No direct correspondence
207-208	Moved 10 nm south of Westland arrivals
209-210	Overlies New River arrivals

Post-1982 Departure Routes	1972 Departure Areas
310-301	Overlies Bradley & Oakland departure areas
302-303	Overlies Nimrod & Guppy departure areas
304-305	Overlies Cutler departures
306-307	Overlies Marathon & Perrine departure areas
308-309	Moved several miles south of the Cypress departure area

The design of the terminal maneuvering area routes generally correspond to those that are in use at the present time in Miami. Some changes were made in the areas south of the airport to account for the revised route structure in that area. However, the procedures are essentially mirror images of the procedures that are used in northern sectors of the terminal area. A 45° divergence angle was used for all departures on the parallel runways in order to conform with accepted ATC practice.

The use of the low altitude arrival waypoint was retained in these final designs. The primary use of this waypoint is for a center/approach control handoff point or for use as a holding fix. If there is no operational need for this waypoint then the arrival route can be shortened slightly to permit direct downwind or base leg entries to the terminal maneuvering area.

7.5.2.5 Final Post-1982 San Francisco Design

The final post-1982 San Francisco terminal area designs are shown in Figure 7.66 and 7.67. The waypoint locations on the 45 nm boundary of the San Francisco area were determined from the optimum waypoint location program.

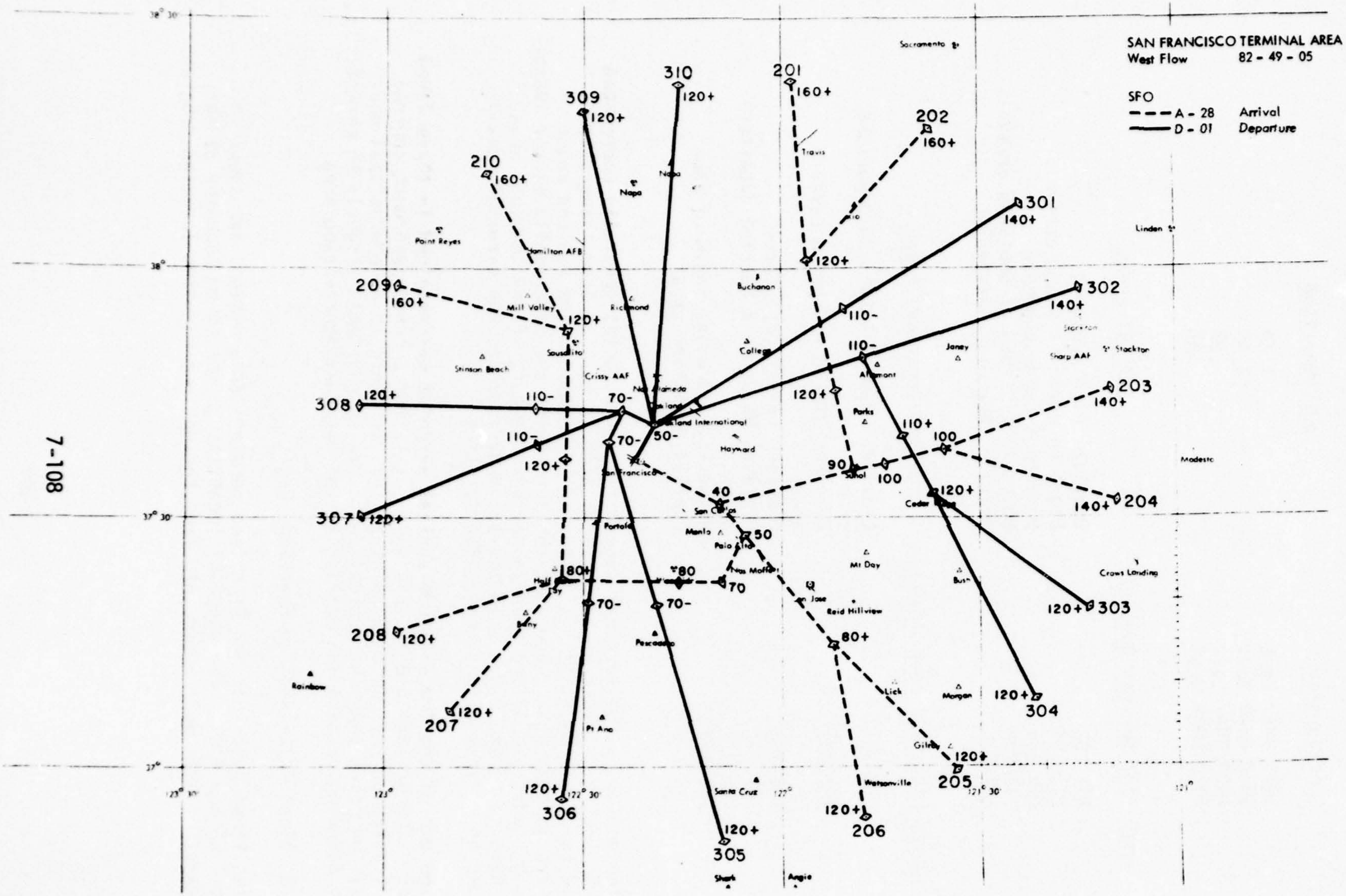


Figure 7.66 San Francisco Terminal Area - Final Post-1982 RNAV Design, West Flow

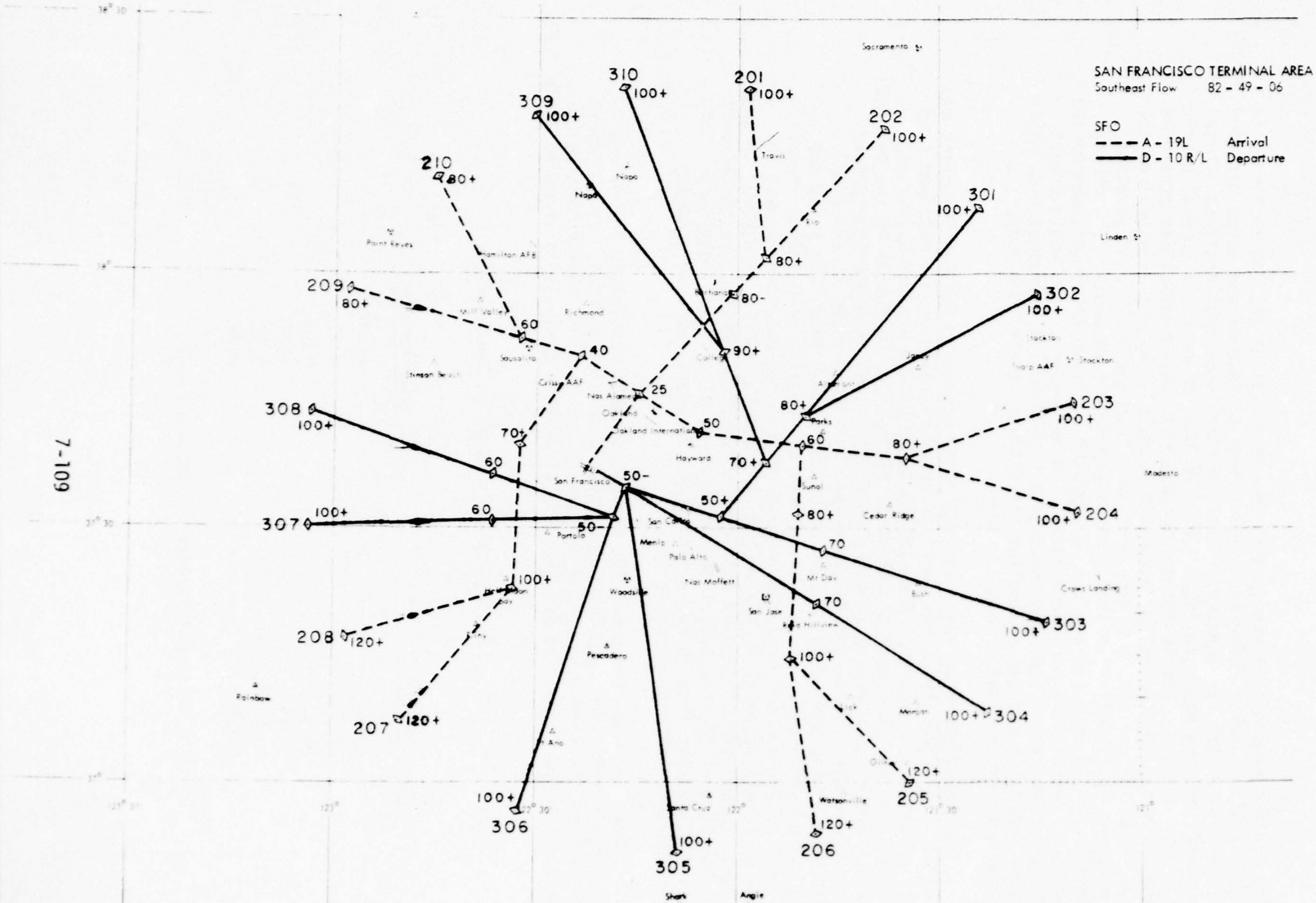


Figure 7.67 San Francisco Terminal Area - Final Post-1982 RNAV Design, Southeast Flow

The traffic sample that was used in the optimization program is listed in Table 7.21. Several different combinations of sectors and waypoints were considered in the development of the optimized post-1982 designs. These combinations are shown in Table 7.22. As was the case for several of the modified designs, the 10 sector, 20 waypoint configuration was chosen as the basis for developing the optimized post-1982 designs. Several of the post-1982 arrival and departure waypoints from the 10/20 configuration corresponded closely with 1972 arrival and departure areas. The choice between the 20 waypoint and the 30 waypoint configurations was made on the basis of operational considerations. The 30 waypoint case would create too many routes and too much congestion throughout the terminal area which would result in reduced controller flexibility rather than increased efficiency of terminal area operations.

The development of the post-1982 route structure for San Francisco was initiated by identifying the terminal boundary waypoints as obtained from the optimization program. From the location of the arrival waypoints, feeder fix locations were placed about 25 nm from the center of the terminal area. The final approach area was then determined from the appropriate arrival runway. Routes which connected the feeder fixes to the final approach course were developed which avoided noise sensitive areas and potential conflict areas in the vicinity of other major Bay Area aiports. Departure routes were designed to proceed from the departure runway to the departure waypoint in the most direct route that was feasible. In some cases it was not possible to make direct departure routes from the airport to the edge of the terminal area due to areas of potential conflict. This was particularly true in the vicinity of the final approach area for Oakland International Airport.

After the modified post-1982 design had been completed, the excess distance values were calculated for these finalized designs. In addition the excess distance values were calculated for the 1972 RNAV routes which were discussed in Section 5. The results of this analysis is shown in Table 7.23.

Table 7.22 Waypoint Optimization Results for San Francisco

Sectors/Waypoints	ΔD/Operation
8/24	0.53
10/20	0.52
10/30	0.34
8.24 E.S.*	1.05
10/20 E. S.	0.76
10/30 E. S.	0.44

* E. S. - Equal Sector Size Constraint Imposed

Table 7.21 San Francisco Traffic Exchanges-High Altitude Jet Traffic

From	Number of Flights	Bearing	From	Number of Flights	Bearing
Seattle, Wash.	15	0.2	New Orleans, La.	1	96.4
Spokane, Wash.	2	18.0	Albuquerque, N.M.	3	96.6
Calgary, Alta.	1	20.8	Houston, Texas	3	100.7
Boise, Idaho	2	36.1	Las Vegas, Nev.	12	102.7
Reno, Nev.	5	46.5	San Antonio, Texas	1	105.0
Minneapolis, Minn.	6	62.2	Fresno, Calif.	2	110.9
Salt Lake City,	5	65.3	Phoenix, Ariz.	10	113.2
Boston, Mass.	2	66.4	Tuscon, Ariz.	3	116.9
Milwaukee, Wis.	1	67.5	Palm Springs, Calif.	1	126.7
Detroit, Mich.	3	68.7	Bakersfield, Calif.	1	128.4
Chicago, Ill.	17	69.6	Ontario, Calif.	11	131.2
Kennedy, New York, N.Y.	9	69.7	Burbank, Calif.	20	135.2
Cleveland, Ohio	1	70.1	Santa Ana, Calif.	16	135.7
Philadelphia, Pa.	2	71.4	Long Beach, Calif.	7	136.6
Omaha, Neb.	1	71.4	San Diego, Calif.	10	137.5
Pittsburgh, Pa.	1	71.5	Los Angeles, Calif.	112	137.6
Baltimore, Md.	2	72.9	Santa Barbara, Calif.	4	146.5
Washington, D. C.	6	73.5	San Luis Obispo, Calif.	1	149.0
Denver, Co.	11	75.7	Hilo, Hawaii	1	246.8
Kansas City, Mo.	3	76.9	Honolulu, Hawaii	12	252.1
St. Louis, Mo.	1	77.4	Arcata, Calif.	4	338.9
Atlanta, Ga.	2	85.7	Eugene, Ore.	5	354.6
Oklahoma City, Okl.	1	88.8	Medford, Ore.	3	355.5
Modesto, Calif.	0	89.6	Vancouver, B.C.	4	357.4
Dallas, Texas	13	95.2	Portland, Ore.	15	358.9
Miami, Fla.	1	95.9			

Table 7.23 Excess Distance Comparison for San Francisco

Configuration	ΔD/Operation
1972 RNAV West	4.44 nm/Operation
1972 RNAV Southeast	2.85
1982 RNAV West	0.60
1982 RNAV Southeast	0.60

It is quite apparent that a substantial improvement in reducing excess distance at San Francisco through the use of the modified terminal design guidelines was achieved.

The correspondence between the post-1982 designs and the arrival/departure areas that are in use at the present time are described in the following list.

Post-1982 Arrival Routes	1972 Arrival Areas
201-202	Considerably west of Janey arrivals
203-204	Overlies Modesto arrivals
205-206	Moved considerably east of Big Sur arrivals
207-208	Overlies Briney, Woodside arrivals
209-210	Overlies Point Reyes arrivals

Post-1982 Departure Routes	1972 Departure Areas
301-302	Overlies Linden departures
303-304	Considerably east of Portola departures
305-306	Lies west of Point Ano departures
307-308	Overlies oceanic departures
309-310	Overlies Napa, Red Bluff departures

It can be seen that the correspondence of post-1982 routes with existing arrival and departure areas at San Francisco is somewhat less than that which resulted in the previous four terminals that were considered. The implementation of routes from the post-1982 structure in the current structure will therefore require more adjustments than in the other four terminals. Also further adjustments may be required when the terminal/enroute interface and traffic from other Bay Area airports are considered.

As was the practice in the initial 1982 RNAV route designs, the concept of a low altitude arrival waypoint located about 25 miles from the airport was used. If there is no operational use for such a waypoint, such as may occur in a metering and spacing environment, then this waypoint may be eliminated and the arrival routes can be straightened and thus shortened slightly.

7.5.2.6 Final Post-1982 Chicago Design

The final post-1982 designs for Chicago are shown in Figures 7.68 and 7.69. These designs were created with the aid of the optimum terminal area waypoint location program. The Chicago traffic sample that was used by this program is listed in Table 7.24. Several combinations of sectors and waypoints were considered. These combinations along with their associated excess distance values (ΔD/operation) are shown in Table 7.25. The excess distance values are relatively small for all of the candidate configurations in this complex terminal area. Consequently, the selection of the appropriate configuration for Chicago was based more upon correspondence with existing traffic patterns in the Chicago area rather than the excess distance value in order to minimize implementation problems in the transition phases and provide for early user benefits. When the sector/waypoint combinations were compared to the existing traffic patterns at Chicago, it was determined that the 8 sector, 24 waypoint combination generally corresponded quite well to the existing traffic patterns. Consequently, this configuration was chosen as a basis with which to complete the Chicago terminal areas design for the post-1982 time period.

RNAV terminal area route structures were then developed for the southeast and the northwest flow configurations at Chicago O'Hare. Due to the close correspondence between the existing arrival and departure areas and the optimized waypoint locations, similar terminal area traffic patterns could be developed. Consequently, no difficulties were encountered in providing satisfactory arrival or departure paths for the several terminal area routes.

After the design had been completed, an excess distance computation (ΔD/operation) was performed for both the optimized post-1982 route structure and for the 1972 RNAV route structure. The results of this analysis are shown in Table 7.26. It can be seen that an improvement of between 0.6 and 0.7 nm/operation was obtained. Although this improvement is significant, its relative value does indicate that the existing route structure at Chicago is reasonably efficient insofar as excess distance values are concerned.

Table 7.25 Waypoint Optimization Results for Chicago

Sectors/Waypoints	ΔD/Operation
8/24	0.85
10/20	0.90
10/30	0.66
8/24 E. S.*	1.22
10/20 E. S.	1.18
10/30 E. S.	0.79

*E. S. – Equal Sector Size Constraint Imposed

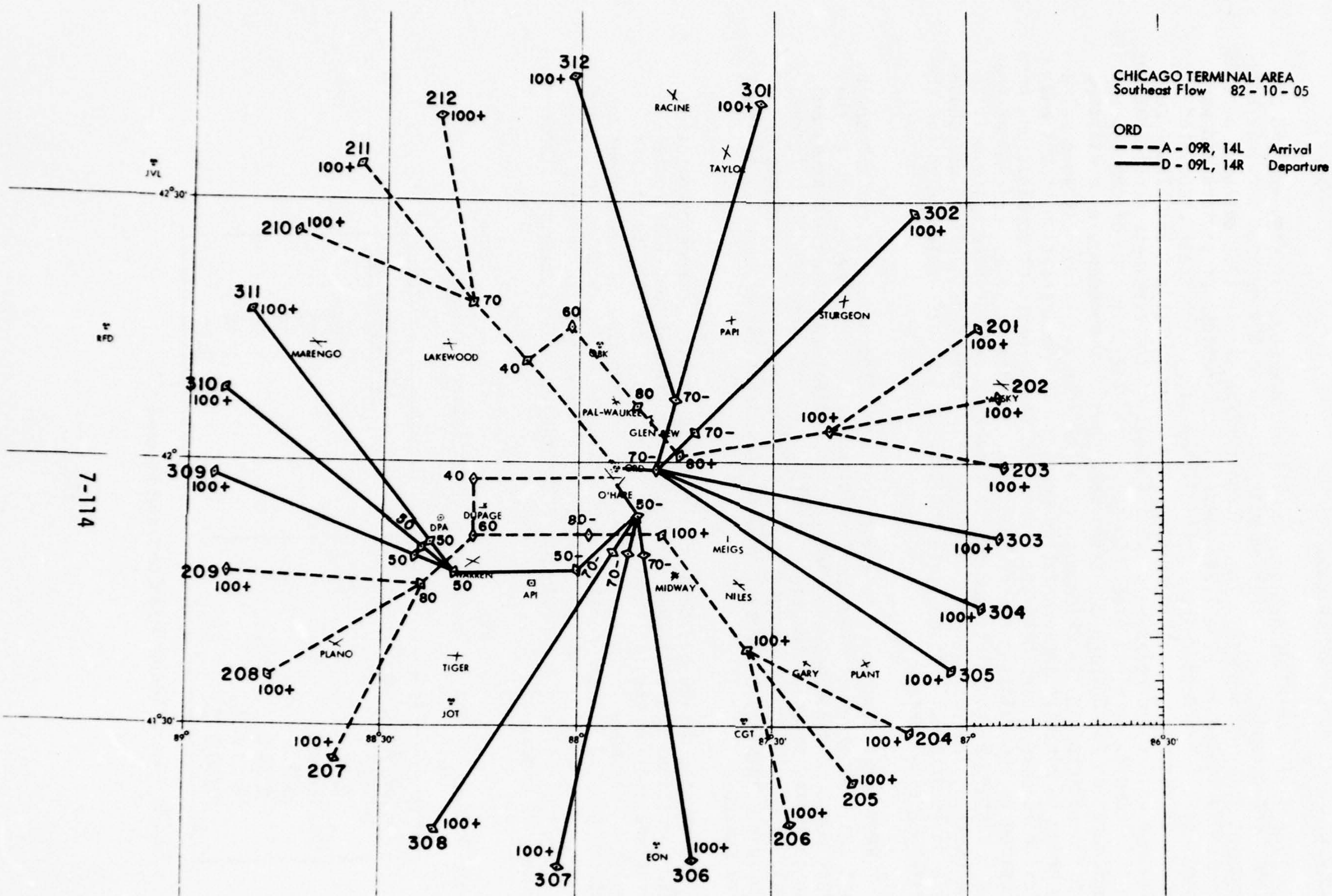


Figure 7.68 Chicago Terminal Area – Final Post-1982 RNAV Design, Southeast Flow

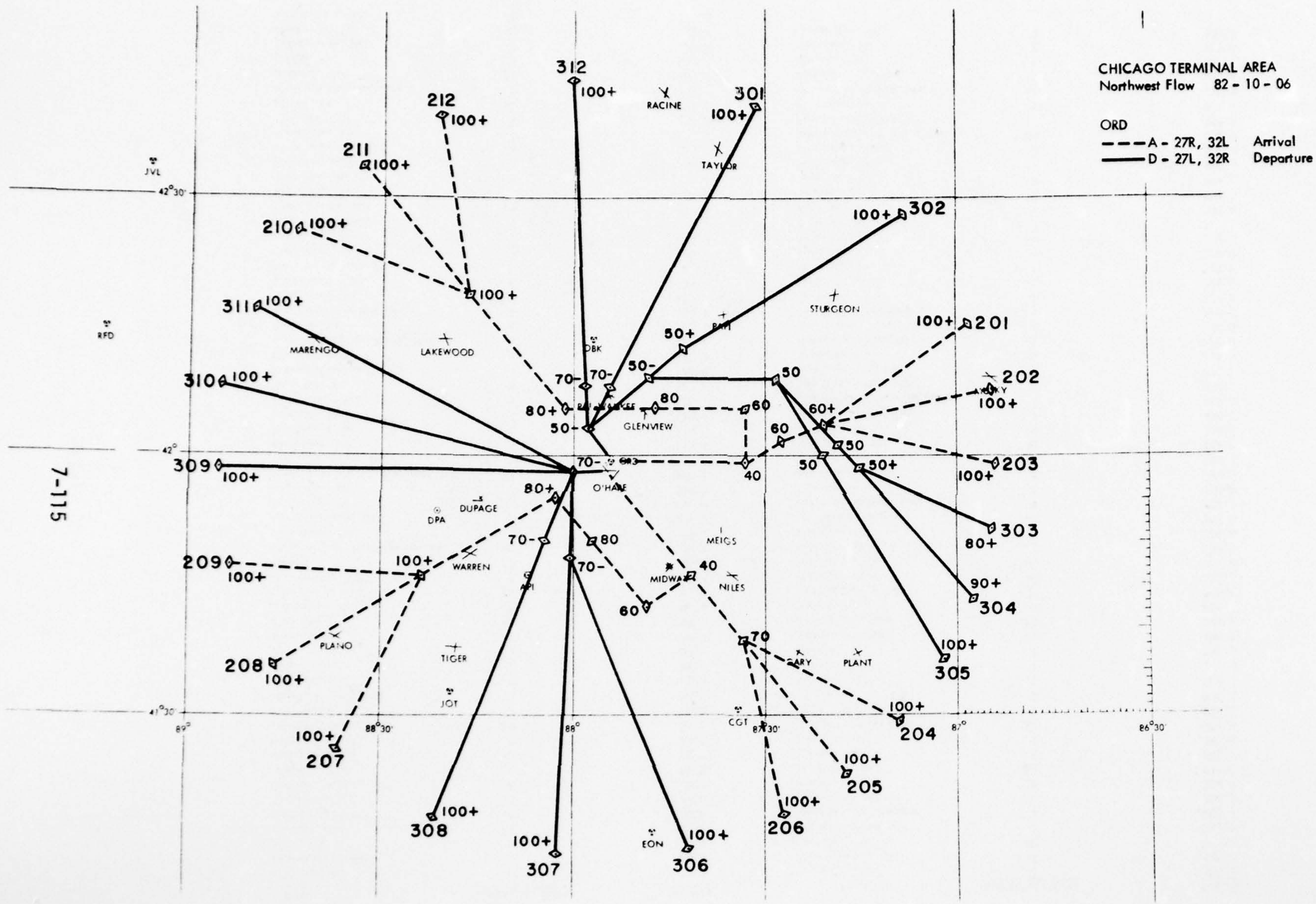


Figure 7.69 Chicago Terminal Area - Final Post-1982 RNAV Design, Northwest Flow

Table 7.24 Chicago O'Hare Traffic Exchanges-High Altitude Jet Traffic

From	Number of Flights	Bearing	From	Number of Flights	Bearing
Saginaw, Mi	4	59.9	Evansville, In.	7	175.8
Montreal, Quebec	5	66.4	New Orleans, La.	3	189.7
Flint, Mi.	1	70.9	Memphis, Tn.	10	193.8
Toronto, Ont	11	71.6	Acapulco, Mexico	1	206.0
Rochester, N.Y.	6	78.0	Mexico City, Mexico	3	206.1
Syracuse, N.Y.	3	78.6	Little Rock, Ar.	1	206.5
Buffalo, N.Y.	8	78.9	Houston, Tx.	8	208.9
Albany, N.Y.	4	81.2	St. Louis, Mo.	23	210.7
Boston, Ma.	15	82.6	Springfield, Il.	1	212.7
Binghamton, N.Y.	4	84.5	San Antonio, Tx.	3	217.8
Detroit, Metro, Mi.	28	84.6	Dallas/Ft. Worth, Tx.	23	221.4
Providence, R.I.	2	85.8	Tulsa, Ok.	4	229.5
Hartford, Ct. (BDL)	9	86.2	Oklahoma City, Ok.	3	232.1
Erie, Pa.	3	86.5	Macomb, Il.	1	235.5
Islip, N.Y.	1	91.2	El Paso, Tx.	1	241.3
La Guardia, N.Y.	30	91.9	Wichita, Ks.	3	242.5
Kennedy, N.Y.	11	92.5	Burlington, Iowa	1	244.6
Newark, N.J.	13	92.6	Kansas City, Mo.	17	244.8
Allentown, Pa.	7	94.0	Tucson, Az.	6	249.1
Cleveland, Oh.	13	95.3	Albuquerque, N.M.	5	250.7
Youngstown, Oh.	3	95.3	Phoenix, Az.	9	253.6
Toledo, Oh.	5	96.2	San Diego, Ca.	6	257.8
Philadelphia, Pa/Wilm'ton De.	12	98.2	Palm Springs, Ca.	2	259.4
Harrisburg, Pa.	1	98.3	Ontario, Ca.	2	261.0
Akron/Canton, Oh.	1	101.1	Los Angeles, Ca.	24	261.5
Pittsburgh, Pa.	28	102.9	Colorado Springs, Co.	1	261.6
Baltimore, Md.	7	104.5	Lincoln, Ne.	2	263.2
Washington, D.C. National	35	107.2	Las Vegas, Nv.	8	263.4
Newport News, Va.	1	115.2	Denver, Co.	17	265.8
Richmond, Va.	3	115.4	Des Moines, Ia.	10	265.9
Ft. Wayne, In.	1	115.5	Omaha, Ne.	9	266.1
Norfolk, Va.	3	115.6	Grand Junction, Co.	1	266.5
Columbus, Oh	8	116.1	Cedar Rapids/Iowa City, Ia.	3	269.2
Danville, Il	8	125.6	San Jose, Ca.	2	271.3
Raleigh/Durham, N.C.	4	127.8	San Francisco, Ca.	21	272.2
Huntington, W.V.	2	129.8	Oakland, Ca.	3	272.3
Greensboro/High Point, N.C.	4	131.0	Honolulu, Oahu; HI.	4	273.8
Muncie, In.	2	132.1	Sacramento, Ca.	2	274.0
San Juan, Puerto Rico	1	135.4	Salt Lake City, Utah	7	274.3
Charlotte, N.C.	3	137.3	Reno, Nv.	1	274.8
Cincinnati, Oh.	11	139.0	Sioux City, Ia.	7	276.6
Tri City Airport, Tn.	1	140.6	Waterloo, Ia.	7	281.2
Columbia, S.C.	1	144.3	Boise, Ia.	1	284.0
Lexington, Ky	1	146.1	Sioux Falls, S.D.	1	286.7
Nassau, Bahamas	1	150.9	Portland, Or.	4	290.1
Indianapolis, In.	4	151.0	Billings, Mt.	1	291.4
Knoxville, Tn.	1	152.5	Seattle, Wa.	9	294.5
Jacksonville, Fl.	1	154.6	Spokane, Wa.	1	295.2
Palm Beach, Fl	2	154.8	Rochester, Mn.	7	301.3
Ft. Lauderdale, Fl.	8	155.7	La Crosse, Wis.	2	308.7
Louisville, Ky.	4	155.8	Minneapolis/St. Paul, Mn.	26	308.7
Orlando, Fl	5	156.3	Ponca City, Okla.	1	319.6
Miami, Fl	11	156.4	Winnipeg, Man.	1	324.0
Montego Bay, Jamaica	1	157.1	Wisconsin, Rapids, Wi.	3	329.9
Atlanta, Ga.	15	160.7	Stevens Point, Wis.	1	335.6
Tampa, Fl.	10	161.0	Wausau, Wi.	1	337.5
Terre Haute, In.	2	169.8	Appleton, Wi.	2	349.0
Nashville, Tn.	6	170.4	Green Bay, Wi.	3	356.2
Birmingham, Al.	2	173.5			

Table 7.26 Excess Distance Comparison for Chicago

Configuration	ΔD/Operation
1972 RNAV Southeast	1.59
1972 RNAV Northwest	1.53
1982 RNAV Southeast	0.86
1982 RNAV Northwest	0.85

The relationship between the post-1982 routes and the 1972 arrival and departure areas is quite close. The correspondence is described in the following list:

Post-1982 Arrival Routes	1972 Arrival Areas
201-202-203	Lies approximately 10 nm south of Papi arrivals
204-205-206	Overlies the Plant, Gary arrivals
207-208-209	Overlies the Plano, Warren arrivals
210-211-212	Overlies the Woodstock arrivals

Post-1982 Departure Routes	1972 Departure Areas
312-301-302	Slightly west of 1972 northbound departures
303-304-305	Overlies Pullman, Keeler and South Bend departures
306-307-308	Overlies Peotone and Roberts departures
309-310-311	Slightly north of Davenport, Polo and Dubuque departures

In each of the arrival sectors the traffic arrives at the terminal boundary at three locations and is then funneled into a low altitude arrival waypoint. If this point is not required for some operational reason such as a handoff point or a holding fix, then the arrival aircraft could proceed directly to the downwind or base leg and thus travel over a shorter, straighter flight path.

7.5.2.7 Final Post-1982 New York Design

The route structure for the post-1982 New York terminal area designs are shown in Figures 7.70 and 7.71. These designs were made with the aid of the optimum terminal area waypoint location program. However, unlike those designs that were developed for the other six terminal areas, a considerable number of liberties were taken with the waypoint locations that were developed by this program. In general these variations were necessary due to the requirement to accommodate traffic to and from all three of the major terminal areas rather than a single major airport as was the case in the previous terminal areas.

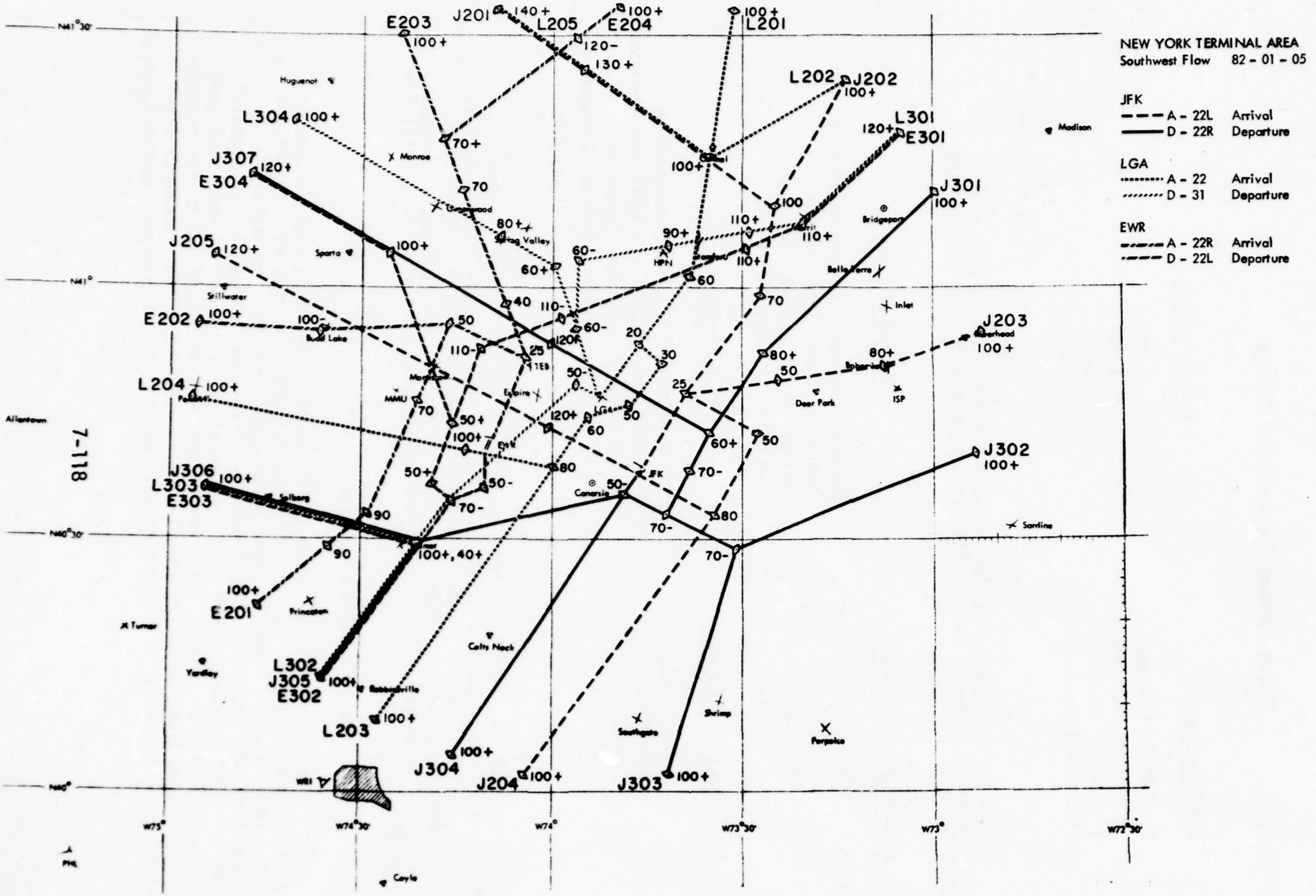


Figure 7.70 New York Terminal Area - Final Post-1982 RNAV Design, Southwest Flow

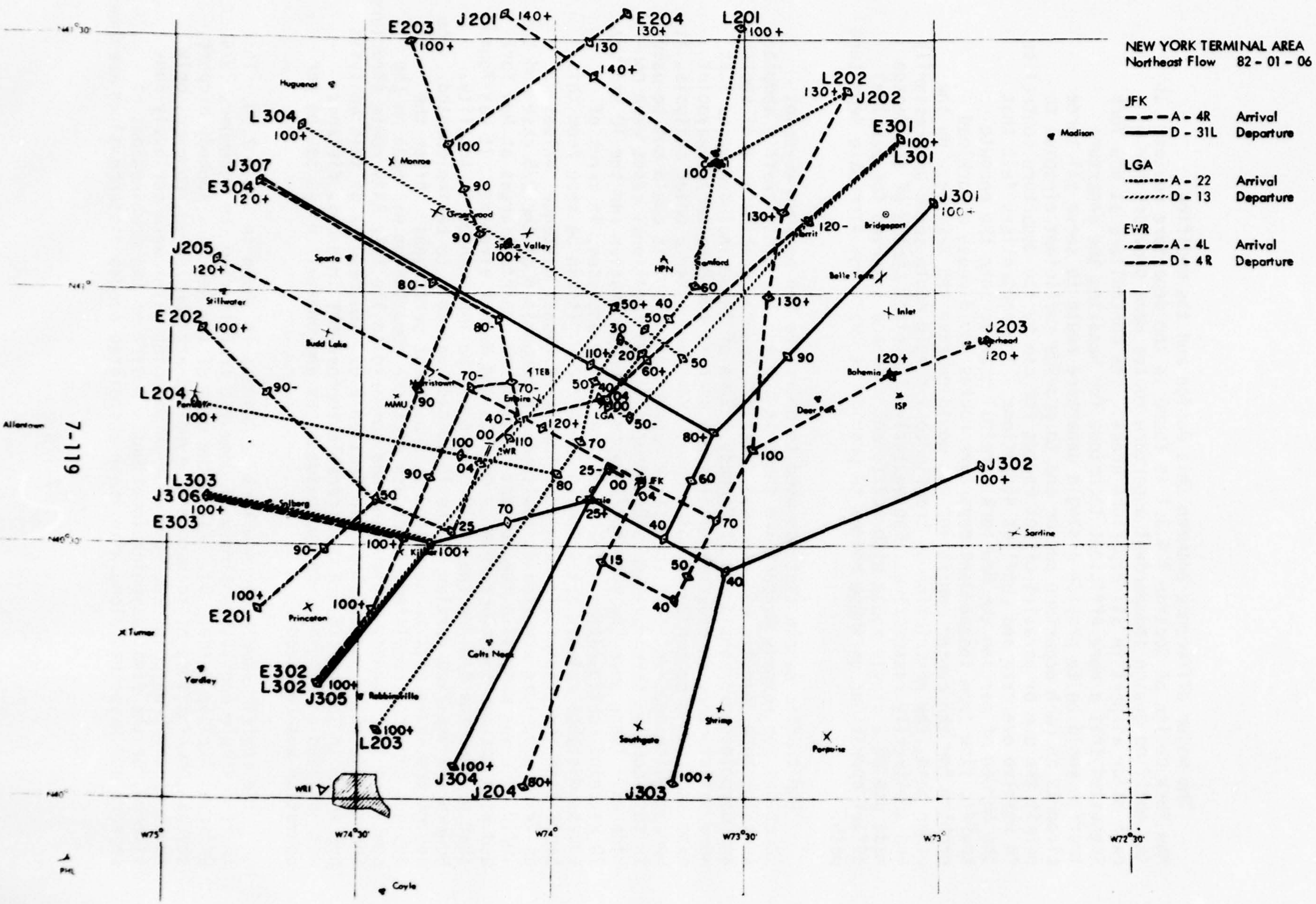


Figure 7.71 New York Terminal Area - Final Post-1982 RNAV Design, Northeast Flow

The major difference between this design and the modified New York design of Section 7.4.3.1 is found in the departure routes. In the modified design independent departure routes were provided for each major airport in all departure areas. The controllers at New York suggested that a more efficient technique for handling the departure traffic would be to provide a single departure route to serve all three airports in each departure sector and to provide sufficient airspace to permit the use of parallel offset routes for use by the departure controller to resolve overtake and conflict situations. The controllers felt that the burden of merging the New York terminal traffic into the enroute traffic flow from independent departure routes would cause a workload problem for the center controller who would receive the traffic. On the other hand, the restriction of traffic to a single route seems unnecessarily and arbitrarily restrictive. Consequently, the final choice of the design made use of a single route with sufficient airspace reserved for parallel offset operations on these routes to provide at least one alternate departure path.

The traffic sample that was used to determine the optimum waypoint locations for Kennedy Airport are shown in Table 7.27. This traffic sample contains both domestic and overseas traffic. Several combinations of sectors and waypoints are considered at Kennedy. Some of these included cases that were satisfactory in other terminal areas such as the 8 sector/24 waypoint case and the 10 sector/30 waypoint case. However, after a brief analysis, it became quite apparent that such large numbers of waypoints could not be used in this complex terminal area. Consequently, two additional cases were considered. These were the 8 sector/8 waypoint configuration and the 10 sector/10 waypoint configuration. The results of these analyses, in terms of excess distance values, are shown in Table 7.28. It can be seen from this table that the predictable result of increased excess distance values as fewer waypoints are used is realized. A comparison of the 8/8 case and the 10/10 case was made with the current arrival and departure areas at New York and with optimum locations from La Guardia and Newark airports. It was found that neither the 8/8 nor the 10/10 case could be implemented in totality. However, a modified version of the 10/10 case was able to be implemented. The design procedure will be described in subsequent paragraphs. After the designs had been completed, an excess distance computation was made on the completed 1982 Kennedy designs and was compared to the 1972 RNAV route structure for Kennedy which was developed in Section 5.0. The results of this analysis are shown in Table 7.29. A considerable improvement in excess distance was achieved at Kennedy. An approximate one and one-half miles saving per operation was realized.

The traffic sample for New York La Guardia is shown in Table 7.30. This traffic sample consists entirely of domestic traffic from the December, 1974 Official Airline Guide [15]. As in the case of the New York Kennedy airport, several combinations of sectors and waypoints are considered, however, only the 8 sector/8 waypoint and 10 sector/10 waypoint cases were seriously considered for the final waypoint locations. A list of the combinations of sectors and waypoints along with their associated excess distance values are shown

Table 7.27 New York Kennedy Traffic Exchanges-High Altitude Jet Traffic

From	Number of Flights	Bearing	From	Number of Flights	Bearing
Montreal, Que.	8	2.6	Freeport, Bahamas	1	197.1
Quebec, Que.	1	16.7	Ft. Lauderdale, Fla.	9	201.3
Reykjavik, Iceland	1	34.2	Miami, Fla.	15	201.4
Bergen, Norway	1	39.1	W. Palm Beach, Fla.	4	201.8
Copenhagen, Denmark	1	45.2	Norfolk, Va.	3	205.3
Glasgow, Scotland	1	46.5	Orlando, Fla.	4	208.7
Amsterdam, Netherlands	4	48.9	Newport News, Va.	1	209.6
Cologne, Germany	1	50.0	Sarasota, Fla.	2	210.7
Brussels, Belg.	2	50.9	Tampa, Fla.	7	211.6
London, Eng.	9	51.3	Charleston, S.C.	1	213.7
Shannon, Ireland	1	51.6	Jacksonville, Fla.	2	213.9
Boston, Mass.	7	53.1	Richmond, Va.	1	219.9
Paris, France	6	53.8	Charlotte, N.C.	1	227.0
Frankfurt, Germany	3	55.2	Washington, D.C.	16	232.1
Milan, Italy	2	55.2	Mexico City, Mexico	3	232.7
Rome, Italy	3	57.4	Atlanta, Ga.	7	232.8
Madrid, Spain	2	65.8	Baltimore, Md.	4	233.5
Lisbon, Portugal	1	70.0	New Orleans, La.	3	236.0
Malaga, Spain	1	70.3	Houston, Texas	3	244.9
Athens, Greece	1	77.3	Nashville, Tenn.	1	249.1
Terceira, Azores	1	77.7	Dallas/Ft. Worth, Texas	5	254.2
Dakar, Senegal	1	101.1	Pittsburgh, Pa.	3	268.5
Rio De Janeiro, Brazil	1	150.0	Phoenix, Ariz.	3	268.7
Barbados, W. Indies	2	151.4	San Diego, Calif.	1	270.9
Antigua, W. Indies	4	152.7	Los Angeles, Calif.	11	273.6
Fort De France, Martinique	1	153.2	Las Vegas, Nev.	2	275.2
Sao Paulo, Brazil	1	153.3	Denver, Co.	4	277.7
St. Martin, Neth. Antilles	1	154.5	Cleveland, Ohio	3	278.5
Port of Spain, Trinidad	1	156.6	Omaha, Neb.	1	279.0
St. Croix, Virgin Island	4	158.6	Chicago, Ill.	11	281.1
San Juan, P. R.	11	161.1	San Francisco, Calif.	10	281.4
Caracas, Venezuela	2	166.5	Salt Lake City, Ut.	1	282.7
Buenos Aires, Argentina	1	167.0	Honolulu, Hawaii	1	283.0
Curacao, Neth. Antilles	1	170.0	Detroit, Mich.	3	284.5
Santo Domingo, Dom. Rep.	2	170.0	Milwaukee, Wis.	1	286.3
Aruba, Neth. Antilles	2	172.0	Seattle, Wash.	2	297.6
Port Au Prince, Haiti	1	176.0	Buffalo, New York	2	302.5
Bogota, Columbia	1	180.2	Toronto, Ont. (Can.)	7	306.2
Barranquilla, Columbia	1	181.8	Winnepeg, Manitoba	1	307.1
Kingston, Jamaica	3	187.0	Rochester, N.Y.	1	311.1
Montego Bay, Jamaica	4	190.0	Anchorage, Alaska	1	321.5
Panama City, Rep. of Panama	1	190.4	Syracuse, N.Y.	2	325.8
Nassau, Bahamas	3	191.7	Fairbanks, Alaska	1	326.1

Table 7.28 Waypoint Optimization Results for New York Kennedy

Sectors/Waypoints	ΔD/Operation
8/8	3.13
10/10	2.08
8/24	0.69
10/30	0.58
8/24 E.S.*	1.11
10/30 E.S.	0.69

*E.S. - Equal Sector Size Constraint Imposed

Table 7.29 Excess Distance Comparison for New York Kennedy

Configuration	ΔD/Operation
1972 RNAV Southwest	4.34
1972 RNAV Northeast	4.34
1982 RNAV Southwest	2.78
1982 RNAV Northeast	2.78

in Table 7.31. The waypoint locations as determined by the waypoint optimization program were not used directly. These locations were noted and an attempt was made to align the arrival and departures with these optimum locations to the extent possible without interfering with routes from the other two major airports.

Once the post-1982 route structures for both the northeast and southwest flow for New York were completed, an excess distance computation was performed on both the new post-1982 route structures. The results of this analysis are shown in Table 7.32. It can be seen that a very slight improvement was obtained for the Δ D/operation value for La Guardia traffic in the post-1982 configuration. However, the values of excess distance that were obtained are slightly better than those of Kennedy and Newark airports thus indicating a relatively good route alignment exists currently at La Guardia.

Table 7.31 Waypoint Optimization Results for New York La Guardia

Sectors/Waypoint	ΔD/Operation
8/8	2.25
10/10	1.50
8/24	0.76
10/30	0.64
8/24 E.S.*	1.22
10/30 E.S.	0.83

*E.S. - Equal Sector Size Constraint Imposed

Table 7.30 New York La Guardia Traffic Exchanges-High Altitude Jet Traffic

From	Number of Flights	Bearing	From	Number of Flights	Bearing
Montreal, Quebec	5	2.6	Nashville, Tenn.	2	249.1
Burlington, Vt.	3	8.4	Charleston, W. Va.	2	250.3
Lebanon, N.H.	3	22.2	Memphis, Tenn.	3	250.8
Keene, N.H.	1	29.5	Dallas, Ft. Worth, Tx.	8	254.2
Augusta, Me.	1	39.3	Harrisburg, Pa.	1	256.6
Portland, Me.	3	41.8	Louisville, Ky.	2	257.9
Boston, Mass.	12	53.1	Oklahoma City, Ok.	1	261.5
New Bedford, Mass.	1	67.3	Cincinnati, Oh.	6	261.6
Ft. Lauderdale, Fl.	8	201.3	Tulsa, Okla.	1	262.1
Miami, Fl.	11	201.4	St. Louis, Mo.	7	266.2
W. Palm Beach, Fl.	3	201.8	Columbus, Oh.	5	266.3
Norfolk, Va.	3	205.3	Dayton, Oh.	4	266.9
Orlando, Fl.	2	208.7	Indianapolis, Ind.	4	267.6
Tampa, Fl.	2	211.6	Pittsburgh, Pa.	14	268.5
Jacksonville, Fl.	1	213.9	Kansas City, Mo.	2	271.5
Raleigh/Durham, N.C.	5	219.4	Ontario, Calif.	2	273.3
Richmond, Va.	3	219.9	Akron/Canton, Oh.	1	273.7
Columbia, S.C.	2	222.1	Greensboro/High Point, N.C.	3	277.1
Charlotte, N.C.	4	227.0	Cleveland, Oh.	11	278.5
Greenville/Spartanburg, S.C.	1	230.7	Chicago, Ill.	33	281.1
Lynchburg, Va.	1	231.6	Detroit, Mi.	12	284.5
Washington, D.C.	27	232.1	Milwaukee, Wis.	7	286.3
Atlanta, Ga.	12	232.8	Bradford, Pa.	1	287.4
Baltimore, Md.	3	233.5	Minneapolis/St. Paul, Minn.	7	292.6
Charlottesville, Va.	2	234.4	Saginaw, Mich.	1	293.4
Roanoke, Va.	2	235.6	Buffalo, N.Y.	5	302.5
New Orleans, La.	2	236.0	Toronto, Ont.	7	306.2
Birmingham, Ala.	2	238.8	Rochester, N.Y.	5	311.1
Knoxville, Tenn.	2	241.1	Syracuse, N.Y.	3	325.8
Houston, Tx.	4	244.9	Utica, N.Y.	1	335.6

Table 7.32 Excess Distance Comparison for New York La Guardia

Configuration	ΔD/Operation
1972 RNAV Southwest	2.05
1972 RNAV Northeast	2.05
1982 RNAV Southwest	1.99
1982 RNAV Northeast	1.97

The traffic sample that was used to determine the optimum waypoint location at Newark is shown in Table 7.33. As in the case for both Kennedy and La Guardia, the location of the terminal waypoints as determined by this technique could not be used directly. Instead consideration had to be given to arrival and departure routes for the other two major airports at New York. A list of the combinations of sectors and waypoints that were applied to the Newark traffic sample is shown in Table 7.34. Again the 8/8 and the 10/10 cases are indicative of excess distance values that can be expected when the routes from all of the major airports are considered. An analysis of the optimum waypoint locations indicated that the 10 sector case was more appropriate as a design basis than was the 8 sector/8 waypoint case.

After the New York route structures were developed for all three major airports, an excess distance computation was made for Newark. The results of this analysis are shown in Table 7.35. It can be seen that a slight improvement in excess distance (ΔD/operation) was obtained in the post-1982 design.

Table 7.34 Waypoint Optimization Results for Newark

Sectors/Waypoints	ΔD/Operation
8/8	2.40
10/10	1.74
8/24	0.60
10/30	0.55
8/24 E.S.*	1.07
10/30 E. S.	0.63

*E. S. - Equal Sector Size Constraint Imposed

Table 7.35 Excess Distance Comparison for Newark

Configuration	ΔD/Operation
1972 RNAV Southwest	3.20
1972 RNAV Northeast	3.20
1982 RNAV Southwest	3.00
1982 RNAV Northeast	3.00

Table 7.33 Newark Traffic Exchanges - High Altitude Jet Traffic

From	Number of Flights	Bearing
Bedford, Mass.	1	48.5
Boston, Mass.	6	53.1
San Juan, Puerto Rico	4	161.1
Nassau, Bahamas	1	191.7
Ft. Lauderdale, Fl.	7	201.3
Miami, Fl.	8	201.4
W. Palm Beach, Fl.	1	201.8
Norfolk, Va.	3	205.3
Orlando, Fl.	2	208.7
Tampa, Fl.	1	211.6
Jacksonville, Fl.	1	213.9
Raleigh/Durham, S.C.	1	219.4
Richmond, Va.	1	219.9
Columbia, S.C.	1	222.1
Charlotte, N.C.	4	227.0
Washington, D.C.	14	232.1
Atlanta, Ga.	9	232.8
Baltimore, Md.	2	233.5
Roanoke, Va.	1	235.6
New Orleans, La.	1	236.0
Hazleton, Pa.	1	242.2
Houston, Tx.	1	244.9
Dallas/Ft. Worth, Tx.	6	254.2
Louisville, Ky.	1	257.9
St. Louis, Mo.	2	266.2
Columbus, Oh.	2	266.3
Indianapolis, Ind.	2	267.6
Pittsburgh, Pa.	11	268.5
Los Angeles	3	273.6
Greensboro/High Point N.C.	5	277.1
Youngstown, Oh.	1	277.5
Denver, Co.	3	277.7
Cleveland, Oh.	6	278.5
Toledo, Oh.	1	279.3
Chicago, Ill.	12	281.1
San Francisco, Calif.	1	281.4
Williamsport, Pa.	1	282.2
Detroit, Mi.	7	284.5
Buffalo, N.Y.	5	302.5
Rochester, N.Y.	3	311.1
Syracuse, N.Y.	3	325.8

The design procedure made use of several types of information concerning the terminal areas. First, the existing arrival and departure areas were considered. Second, the waypoint locations as determined from the optimum waypoint location program were considered, and third, the route structure that was developed in Section 7.4 for the New York area, southwest flow, was considered. This route structure had been subjected to analysis by the New York controllers and was discussed in some detail during the terminal area briefings. Their major comment on this design was concerned with the multiple departure routes that were shown leaving the terminal area in all of the departure areas. The controllers commented that a better technique of departure route design would be to include only one or two charted routes but provide sufficient airspace for parallel offset routes that could be used in tactical situations by the controller. Thus the near optimum charted route could be used while some controller flexibility would be available in order to handle conflict and overtake situations.

The design procedure that was ultimately used at New York was based generally on existing arrival and departure areas. The optimum waypoint locations for each of the three major airports were determined, and in areas where airspace was available, the current routes were moved to a position which was closer to the optimum location than in the 1972 RNAV design. Routes in the terminal maneuvering area in the post-1982 design corresponded closely to existing radar vector paths. Insofar as altitude restrictions were concerned, considerable use of the distance altitude profiles for both climbing and descending aircraft were used. In general the altitudes on the modified 1982 routes are slightly higher than those that are used at the present time.

The correspondence between the existing arrival and departure fixes at New York and the post-1982 modified route structure was analyzed. The following list of post-1982 routes has a reasonably close correspondence with several of the existing arrival/departure areas:

Post-1982 Arrival Routes	1972 Arrival Areas
J201- J202	West of Carmel arrivals
J203	Overlies Bohemia arrivals
J204	Slightly east of Southgate arrivals
J205	Slightly south of Empire arrivals
L205-L201-L202	Overlies Carmel arrivals
L203	Near Robbinsville arrivals
L204	Overlies
E201	Slightly west of Princeton arrivals
E202	Overlies Budd Lake arrivals
E203-E204	Slightly east of Monroe arrivals

Post-1982 Departure Routes	1972 Departure Areas
J301	Overlies Belle Terre departures
J302	Overlies oceanic departures
J303	Near Shrimp departures
J304	Near Colts Neck departures
J305	Near Robbinsville departures
J306	Near Solberg departures
J307	Several miles south of Huguenot departures
L301	Overlies Merrit departures
L302	Slightly west of Robbinsville departures
L303	Overlies Solberg departures
L304	Slightly south of Huguenot departures
E301	Overlies Merrit departures
E302	Slightly west of Robbinsville departures
E303	Overlies Solberg departures
E304	Considerably south of Huguenot departures

The post-1982 route structure at New York in many ways bears a considerable resemblance to the exisitng 1972 VOR/radar vector route structure. However, the use of dedicated RNAV routes has permitted more direct routes to the terminal boundary for the departures and fewer doglegs for the arrival traffic. The use of RNAV has permitted parallel arrival/departure lanes to be used in congested areas to the southwest and to the northwest of the major airports. This, coupled with the use of the parallel offset capability that is inherent with most RNAV avionics systems, helps to create routes which are of benefit to the user but still provide for a degree of flexibility that is essential to the air traffic controller.

7.5.2.8 Comparison of Post-1982 Designs

With the completion of terminal area route structures which are based upon the modified design guidelines, it is possible to directly compare these route structures with those based upon the strict application of the Task Force terminal design concepts that are described in in Sections 7.1.1 through 7.1.7. From an ATC point of view both the Task Force designs and the modified designs should be able to accommodate traffic to and from their respective airports. In terms of airspace utilization both design philosophies produce route structures which have adequate airspace in which to maneuver aircraft for safe and expeditious operations to and from the terminal area. Both design procedures produced routes whose route width requirements were capable of being met by specifications that are in current use as defined by FAA Advisory Circular 90-45A. The major differences between the route structures that are produced by the two design philosophies can be characterized by the following observations. The task force design concept forces traffic to arrive and depart in specific,albeit arbitrary,sectors of the terminal area. The modified guidelines permit traffic to arrive and depart the terminal area in sectors that are selected according to natural traffic flow. The Task Force procedure produces a very stylized, orderly route structure while the modified procedures

produce a route structure which is more operationally flexible for both the controller and the user. In summary, from an ATC standpoint, both design techniques produce satisfactory route structures which should permit safe and efficient operations into and out of the terminal area.

From a user benefit standpoint it would be expected that the ability to align terminal routes according to traffic flow, as prescribed by the modified design guidelines, should result in a user benefit for terminal route structures that are based upon this design technique. In order to validate this assumption a route length and altitude restriction analysis was performed on the post-1982 Task Force designs versus the final post-1982 designs. The techniques which were used in this analysis are described in Section 7.2.2.2 and Reference 3. The results of this analysis are shown in Table 7.36. With the exception of Philadelphia and New Orleans, the benefits shown in Table 7.36 favor the modified route structure concept. New Orleans shows a slight penalty for most aircraft in using the final post-1982 routes while Philadelphia shows a distinct advantage to using the Task Force-derived route structure. A comparison of the route structures at Philadelphia and New Orleans points to longer route lengths in the modified designs as being a definite problem in the final design which causes a significant penalty to the users as compared to the Task Force routes. One potential change in the final design which could reduce the route length problem would be to use an eight sector rather than a ten sector terminal design basis in applying the modified design quidelines at these two terminal areas. The resulting route structure would be expected to be slightly less complex with fewer crossing routes at both Philadelphia and New Orleans. This route structure change could possibly produce benefits for Philadelphia and New Orleans in using the modified rather than the Task Force design guidelines.

7.5.3 User Benefits for Final RNAV Designs

A route length and altitude restriction analysis was performed to determine user benefits for operations at the nine airports (seven terminal areas) for the final designs relative to the current VOR/radar vector routes. Computations are made for both the amended 1972 RNAV route structures which are discussed in the preceding sections and the final 1982 RNAV route structure. The user benefit is obtained by comparing the penalties of operating on the amended 1972 RNAV route structure versus the final 1982 RNAV route structure. It should be noted that the initial route length and altitude restriction analysis compared initial 1982 RNAV designs to initial 1972 designs while this analysis compares final 1982 RNAV designs to amended 1972 designs. One additional distance related consideration was included in the user benefit analysis for the final 1982 designs. The excess distance improvement (Section 7.5.1) of RNAV over VOR was included as a potential distance benefit of the user that is operating in the terminal area. The benefit that is attributed to the excess distance improvement was computed in exactly the same manner as the benefit that is obtained from a shorter route length to or from the airport to the periphery of the terminal area.

Table 7.36 Time and Fuel Benefits-Post-1982 Modified Designs vs Post-1982 Task Force Designs

	AIRCRAFT															
	B747		DC-10		DC-8		B727		DC-9		F.28		F227		LEAR	
AIRPORT	FUEL*	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME	FUEL	TIME
NEW ORLEANS	-39	-.02	-11	-.02	-30	.00	-4	-.02	-3	-.01	-2	.00	-2	+.20	-2	-.03
DENVER	160	.50	129	.49	107	.52	86	.53	62	.56	42	.60	25	.94	14	.56
PHILADELPHIA	-192	-.54	-107	-.51	-121	-.46	-61	-.45	-42	-.40	-30	-.36	-13	.26	-14	-.37
MIAMI	282	.67	169	.66	148	.68	94	.65	65	.67	45	.69	32	1.08	17	.64
SAN FRANCISCO	278	.74	179	.73	137	.76	88	.76	74	.79	38	.80	34	1.48	9	.73
CHICAGO ** O'HARE	314	.91	214	.92	164	.91	127	.94	89	.95	65	1.03	40	1.32	27	1.03
NEW YORK KENNEDY	804	1.95	514	2.00	504	1.90	321	1.86	223	1.90	169	1.98	95	1.68	82	2.06
NEW YORK LA GUARDIA	1099	2.94	614	2.91	628	2.74	277	2.79	246	2.65	167	2.48	96	.69	85	2.63
NEWARK	744	1.88	424	2.08	434	1.75	243	1.75	169	1.68	129	1.65	69	.78	61	1.67
AVERAGE ***	410	1.09	256	1.10	231	1.07	141	1.07	106	1.07	74	1.09	46	1.10	33	1.10

* Positive values indicate benefits of modified designs, negative values indicate a penalty, fuel in pounds, time in minutes.

** Chicago O'Hare benefits include a change in runways used as well as a change in terminal route structure.

*** The average terminal benefit is computed by using a traffic weighting factor for each airport.

The results of the route length altitude restriction and excess distance are shown in Table 7.37. A positive value (benefit) was obtained for both configurations at all nine airports that were considered. In some areas the benefit is considerable. This is particularly true in the congested New York terminal area. The results of the user benefits analysis for the final post-1982 terminal area designs essentially parallel those that were obtained in the modified New York design that was discussed in Section 7.4.3.2. The analysis was expanded to include four additional aircraft. One is a wide-body trijet which is characterized by the DC-10. The second is a short-haul turboprop which is typified by the FH-227 aircraft. The last two aircraft that were considered are typical of high performance business aircraft that could be using these high and medium density terminal areas. Positive benefits were obtained for both flow directions at all nine airports for all eight aircraft.

7.5.4 High Performance Routes for New York

After the final post-1982 New York RNAV terminal designs were developed, the route structure was analyzed to determine if high performance routes could be accommodated in this design. As a result of this analysis, high performance routes were added for all three airports in the southwest flow configuration and to Kennedy only in the northeast flow configuration. These routes are shown in Figures 7.72 and 7.73. Other routes could have been developed for both flows but no significant user benefits would have resulted. For Kennedy a high performance route (J507) was constructed to the northwest in both traffic flows. This route was 6.3 miles shorter than the standard route (J307) serving this area. Aircraft departing Kennedy that can achieve the minimum specified gradient of 450 ft/mile, for altitudes up to 10,000 feet, can utilize this shorter route. The development of a high performance route to the southwest was not successful. There is a considerable amount of crossing traffic in this area from all three airports which essentially blocks the altitudes which are necessary for the high performance routes.

One high performance route (L501) was developed for La Guardia in the southwest flow. This route serves the northeast departures and it is located 4 miles southeast of the conventional RNAV departure route (L301). The La Guardia high performance departure route is 4.2 miles shorter than the conventional RNAV departure route serving the same area. In the southwest flow one Newark departure route (E504) was developed for traffic going to the northwest. This route merges with the Kennedy high performance departure route approximately 25 miles northwest of the Newark airport. Route E504 is is 4.6 miles shorter than route E304.

A route length and altitude restriction analysis was performed on the New York terminal area for aircraft which can utilize the high performance routes. The results of this analysis indicate that some savings in time and fuel can be realized for aircraft which have climb performance characteristics which permit them to use the high performance routes. The results of this analysis are shown in Table 7.38.

Table 7.37 2D RNAV Benefit-Improvement of 1982 RNAV Design over 1972 RNAV Design

Airport	Flow		Savings per operation (average of arrival and departure) (1) (2)															
			DC-9		B-727		DC-8		B-747		DC-10		FH-227		F-28		Lear 25	
	direction	%use	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)	Fuel (lb)	Time (min)
PHL	E	30	23.1	.23	32.9	.24	64.9	.25	98.5	.24	60.4	.25	9.0	.12	14.3	.20	6.6	.21
	W	70	25.3	.27	34.5	.27	55.0	.27	71.6	.26	56.0	.26	8.9	.09	14.6	.22	6.5	.24
DEN	W	80	74.4	.39	62.4	.39	75.0	.38	137.1	.35	95.2	.36	18.4	.67	27.2	.42	9.3	.40
	E	20	30.6	.13	49.4	.08	44.0	.10	32.1	.01	53.6	.08	19.3	.76	28.4	.23	9.9	.20
MSY	E	50	17.1	.22	27.5	.23	65.8	.24	130.6	.29	50.6	.25	7.0	0	12.0	.20	5.4	.17
	N	50	62.0	.70	91.9	.70	58.1	.71	296.4	.71	170.7	.72	29.8	.91	41.4	.73	17.5	.68
ORD	SE	50	13.8	.16	21.0	.17	35.1	.18	62.8	.18	38.7	.18	6.2	.15	10.3	.18	4.7	.17
	W	50	31.3	.33	44.8	.33	60.4	.35	90.5	.35	79.8	.36	13.3	.42	21.2	.33	8.3	.33
MIA	E	70	43.3	.46	58.7	.46	90.3	.45	127.2	.46	89.6	.45	16.9	.30	27.8	.42	12.3	.44
	W	30	67.2	.72	93.6	.72	157.3	.71	266.4	.76	101.0	.72	22.0	.40	44.6	.69	19.3	.69
SFO	W	75	82.2	.92	95.2	.93	169.4	.78	343.4	.94	195.6	.89	30.4	.96	39.0	.85	24.2	.81
	SE	25	45.8	.52	65.6	.46	46.4	.50	102.3	.44	109.2	.44	28.0	1.68	34.6	.65	9.8	.57
JFK	SW	50	249.5	2.52	243.1	2.57	564.4	2.57	959.5	2.63	607.8	2.63	105.5	2.37	170.6	2.60	76.8	2.65
	NE	50	276.3	2.86	385.2	2.82	606.1	2.81	1039.4	2.82	675.7	2.85	123.3	3.14	188.9	2.93	82.8	2.95
LGA	SW	50	309.0	3.17	455.3	3.24	732.8	3.22	1169.0	3.35	764.3	3.37	132.6	2.08	230.1	3.23	109.9	3.37
	NE	50	165.9	1.79	238.1	1.59	383.1	1.68	586.5	1.71	402.3	1.79	67.2	.67	111.0	1.45	54.5	1.56
EWR	SW	50	179.3	1.92	264.3	2.03	489.2	1.97	898.8	2.13	480.6	2.11	71.7	.80	128.5	1.92	62.1	1.97
	NE	50	92.6	1.01	135.3	1.05	254.2	1.05	461.8	1.14	230.5	1.07	33.2	.16	61.4	.88	29.1	.89

(1) The positive values indicate a benefit to the airspace user. (2) all aircraft types do not operate at all airports shown even though data is presented for that operation

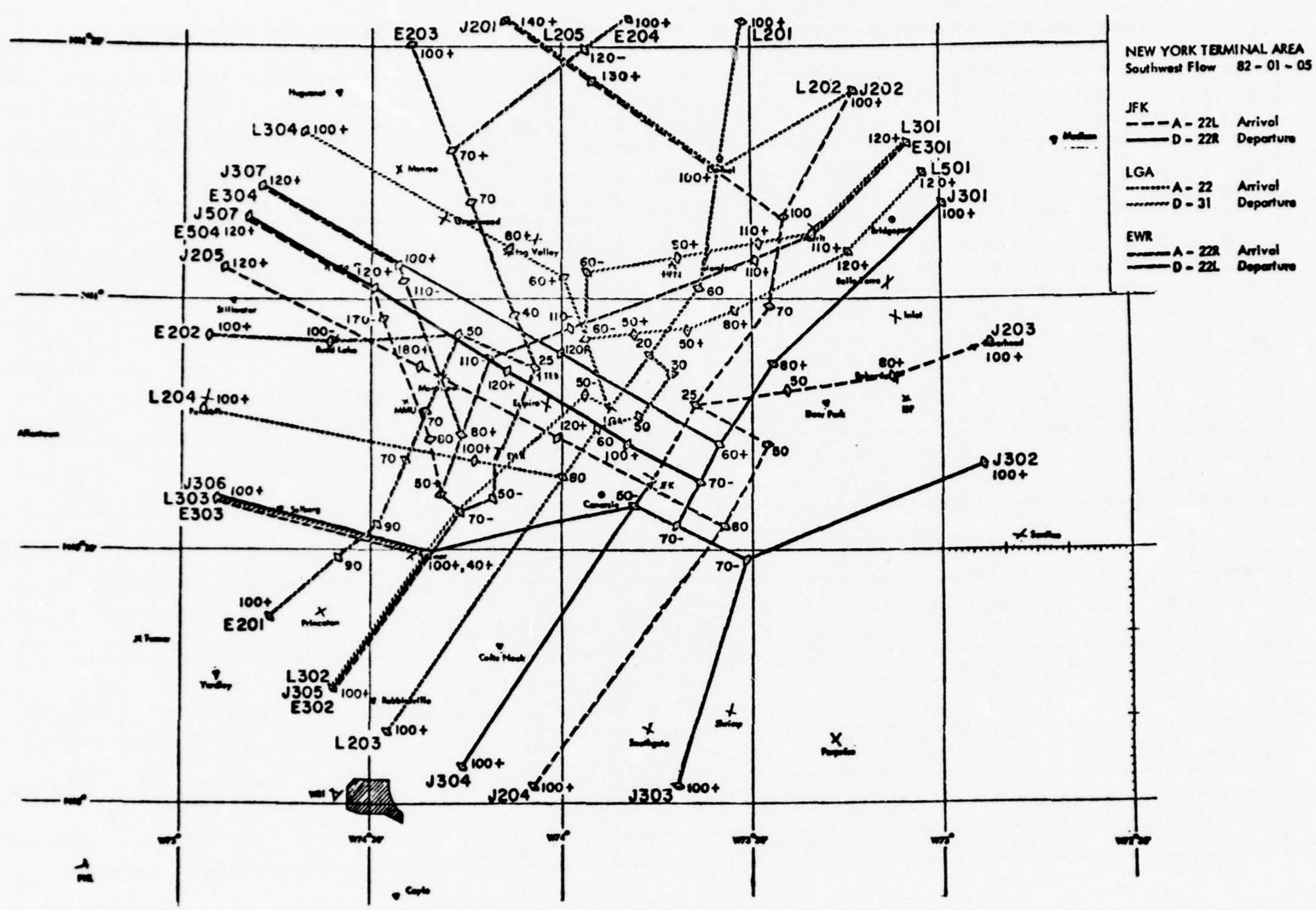


Figure 7.72 Post-1982 RNAV High Performance Routes for New York, Southwest Flow

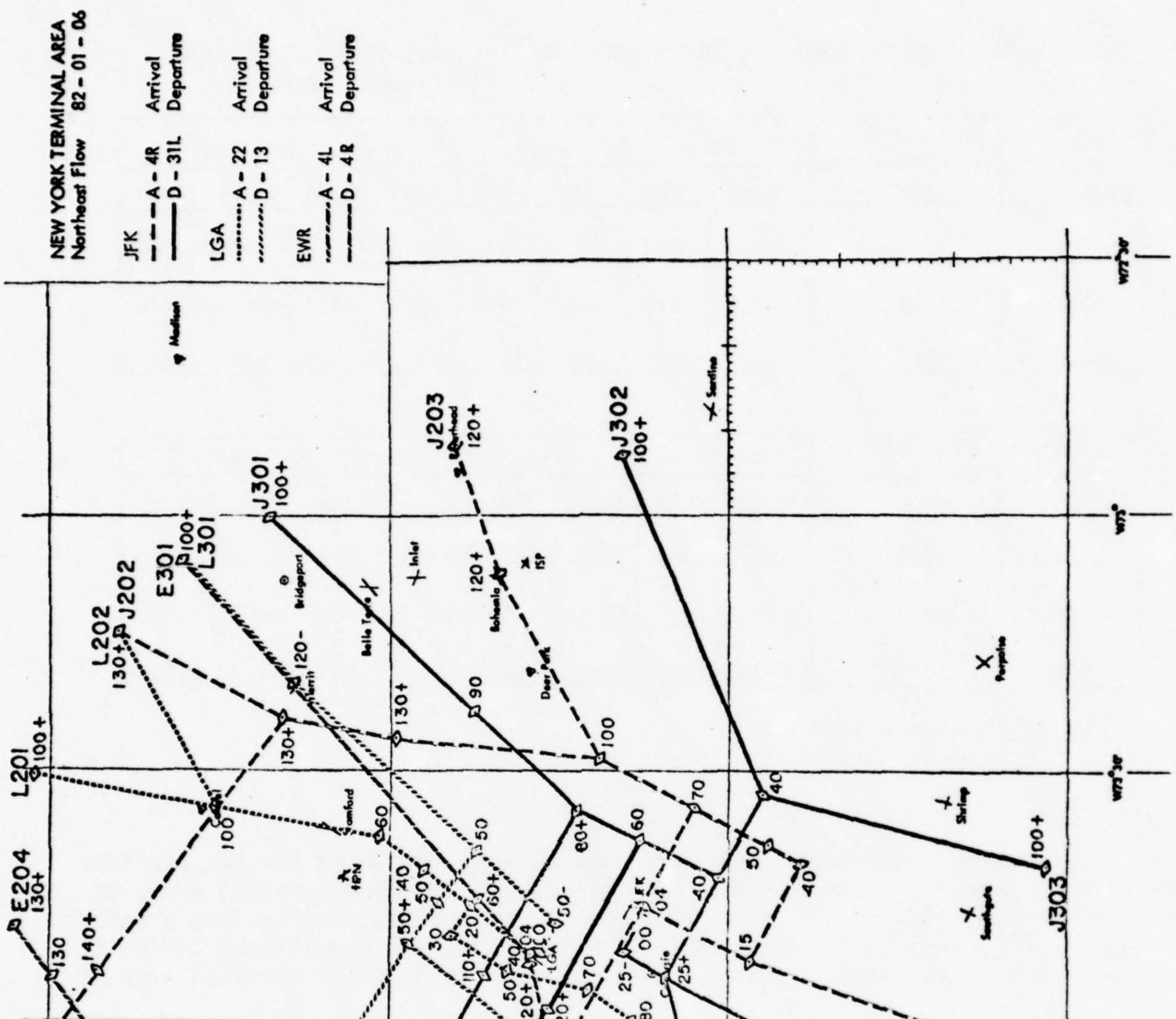


Figure 7.73 Post-1982 RNAV High Performance Routes for New York, Northeast Flow

Table 7.38 High Performance Route Benefits (as compared to Standard Performance Routes)

High Performance Route	Standard Performance Route	DC-9		B727		DC-8		B747	
		Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time
J507	J307	90.8	.822	123.4	.791	191.4	.806	318.0	.767
L501	L301	60.5	.548	82.3	.527	127.6	.537	212.0	.511
E504	E304	66.3	.600	90.1	.577	139.7	.588	232.2	.560

High Performance Route	Standard Performance Route	DC-10		F-28		Lear 25		FH227	
		Fuel	Time	Fuel	Time	Fuel	Time	Fuel	Time
J507	J307	224.2	.781	63.0	.896	23.5	.871	44.2	1.482
L501	L301	149.5	.521	42.0	.597	15.7	.580	29.5	.988
E504	E304	163.7	.570	28.4	.615	0.3	.542	32.3	1.082

/Note/ Fuel in Pounds
Time in Minutes

Although these high performance routes were developed for the New York terminal area only, their use should be considered at other terminal areas as well. The benefits resulting from the use of these routes may be less dramatic in terminal areas less congested than New York, however, significant benefits may be achieved on specific route applications in those other terminal areas.

7.5.5 Summary

The use of the recommended 1982 terminal area design guidelines produced significant improvements in user benefits when compared to those benefits which were obtained in either a strict application of the Task Force design concepts or when compared to the current terminal area procedures which are typified by the 1972 RNAV designs of Section 5.0. Consequently, from a user benefits standpoint the recommended design guidelines provide a considerable potential for savings of both time and fuel at high and medium density airports. The characteristics of these airports were chosen to be purposely broad such that a wide range of problems could be expected to be encountered. Since the final designs provided user benefits in all of these varying terminal areas, it is to be expected that similar benefits could be obtained in terminal areas of comparable size throughout the country. From an ATC standpoint the route structures that were developed using either the Task Force Terminal guidelines or the modified guidelines could be used as a basis for implementing RNAV procedures at the seven terminal areas without any apparent traffic control problems.

8.0 RECOMMENDED POST-1982 TERMINAL AREA DESIGN GUIDELINES

The recommended terminal area design guidelines presented in this section were developed through an iterative procedure of design application and analysis. The Task Force design concept was first used to develop procedures which were utilized in developing an initial set of terminal area designs, both 2D and 3D. User and ATC impact analyses of these initial designs resulted in the development of a set of modified guidelines designed to maximize user economic benefits. The modified guidelines, which evolved into a concept of joint use of terminal airspace by 2D and 3D equipped aircraft, were then reviewed with user groups and FAA field controllers and the resulting design techniques which were developed were applied to a final set of terminal area designs, described in Section 7, and the favorable economic impact of these designs on the users was verified through further analysis.

The recommended terminal area design guidelines which evolved were designed to satisfy the following primary objectives:

1. Design RNAV routes to provide a maximum economic benefit to both 2D and 3D equipped users.

2. Design the enroute-terminal connecting waypoints to serve the high density traffic flows.

3. Design arrival route altitude restrictions to describe vertical envelopes which include optimum descent profiles for several categories of aircraft performance.

4. Design departure route altitude restrictions to describe vertical envelopes which include optimum climb profiles for the total range of aircraft categories using the terminal airspace, and use high performance vertical departure envelopes to provide additional routes where they will prove advantageous to the user.

The purpose of the first objective is to provide an economic benefit for RNAV equipped users. The purpose of the second objective was to overcome the route length penalties that were found in the Task Force terminal designs. In some cases a strict application of the octant concept created route length penalties. The application of the second objective permitted the realignment of octants and, if necessary, the expansion or contraction of an octant as necessary to best serve the traffic flow. The concept of a limited number (but not necessarily the number eight) of alternate arrival and departure areas was retained. High density terminal area operations do require this concept of arrival and departure areas in order to maintain an orderly flow control at the feeder fixes (low altitude arrival waypoints) and the departure gates (low altitude departure waypoints). The purpose of the third and fourth objectives is to provide optimum vertical profiles for 2D equipped aircraft, and to provide additional benefits to 3D equipped users through pilot selection of VNAV gradients, in lieu of imposing the economic penalties associated with fixed gradient VNAV routes.

The high performance vertical departure performance envelopes as stated in the fourth objective were for the purpose of providing a benefit to the

user by including shorter departure routes for high performance aircraft. On routes that require a minimum crossing altitude at some point in order that a shorter route may be taken to the departure waypoint, high performance departure routes can provide both the altitude separation assurance and the shorter route length for aircraft whose performance is adequate to maintain or exceed high performance vertical profiles.

The tools developed for use in the application of the recommended design procedures include:

1) An optimization technique for locating arrival and departure waypoints and sector boundaries, as described in Section 7.5.1

2) A route length and altitude restriction analysis program designed to measure the impact of the design on the time and fuel consumed by the 2D equipped user in the terminal area [3].

3) A technique for measuring the additional time and fuel savings available to 3D equipped aircraft through pilot selection of VNAV gradients [16].

4) A method for determining RNAV and VNAV vertical separation requirements for terminal area designs in order to maximize terminal airspace capacity as summarized in Appendix A.

The application of the guidelines described below must be tempered by consideration of individual terminal area characteristics and the enroute interface, and the final designs should evolve through an iterative design process for maximum user benefit.

8.1 DEVELOPMENT OF THE HORIZONTAL DESIGN

The modified terminal design procedure begins with the development of the horizontal projection (or ground tracks) of the arrival and departure routes to all major airports in the terminal area. (The primary goal is to provide optimum vertical envelopes for all routes, however, a horizontal layout is required as a starting point.) The first task in developing the horizontal design is to define the center and the lateral extent of the terminal area design. For most terminals which have a single major airport, the center of the airport can be used as the center of the terminal complex. Ocassionally in a metroplex area this technique is not satisfactory. The metroplex case will be discussed in a subsequent section.

Once the center of the terminal area has been determined, the terminal area is defined by a radius of approximately 45 nm. Again for metroplex areas it is sometimes necessary to adjust this radius value. Within the terminal complex two areas are defined. One is the terminal transition area and the second is the terminal maneuvering area. Generally, the area within 15-20 nm of the airport contains the terminal maneuvering area while outside of this distance is the terminal transition area. Routes in the terminal transition area remain fixed regardless of which active runways are being used at the airports within the terminal area. Conversely, the routes in the terminal maneuvering area do change as the active runway

in use changes. Once the terminal maneuvering area and the terminal transition area have been defined, the traffic flows can be used to establish the arrival and departure routes.

The routes are set up to apply generally to the octant (or sector) concept as discussed in the Task Force Report. However, the location, the size and the number of the sectors are modified according to the traffic demand. As a starting point the sectors can be aligned according to the Task Force recommendations. However, the orientation of the sectors in the terminal transition area are then changed to accommodate the predominant traffic flows. It is often desirable to locate an arrival-departure sector boundary along a major traffic flow direction in order to keep arrival and departure routes as short as possible. In New York, for instance, the predominant flows are to Boston in the northeast, to Washington in the southwest and to points west such as Chicago, Cleveland, Detroit, Los Angeles and San Francisco. Consequently, the major arrival and departure routes are aligned in these directions for all three major airports. Low and high altitude traffic distribution diagrams are used extensively in this task.

8.2 DEVELOPMENT OF THE VERTICAL DESIGN

8.2.1 Descent Profiles

Waypoint altitudes for the routes were based upon the performance characteristics of several aircraft types under varying conditions. The descent gradient for each aircraft was found to be nearly a constant at 300 feet/mile for descent operations below 10,000 feet. Above 10,000 feet the 300 ft per mile gradient approximates the fuel optimum standard descent and 400 ft per mile gradient approximates the time optimum high speed descent. Consequently, these values were used for estimating descents from all altitudes for all aircraft types. In order to accommodate high speed descents, deceleration segments at a level altitude (usually 10,000 ft.) are required. These segments are 8 to 10 nm in length. Typical descent profiles were shown in Figure 7.41 in the preceding section of this report.

8.2.2 Climb Profiles

The climb profiles varied widely depending on aircraft type, ambient temperature, aircraft weight and climb airspeed. Several typical profiles are shown in Figure 8.1. From these profiles a conventional climb performance envelope was established by using the high and low performance curves for the air transport aircraft represented in Figure 8.1. These profiles were approximated by constant gradients for ease of construction and description purposes. These gradient values are shown in Table 8.1. Performance profiles for the lightweight transport jet were selected as a representative of the high performance profile. Performance profiles for the four engine wide body jet were representative of the low performance profiles. These profiles formed the basis for the conventional climb performance envelope "floor" and "ceiling" which is described by Table 8.1.

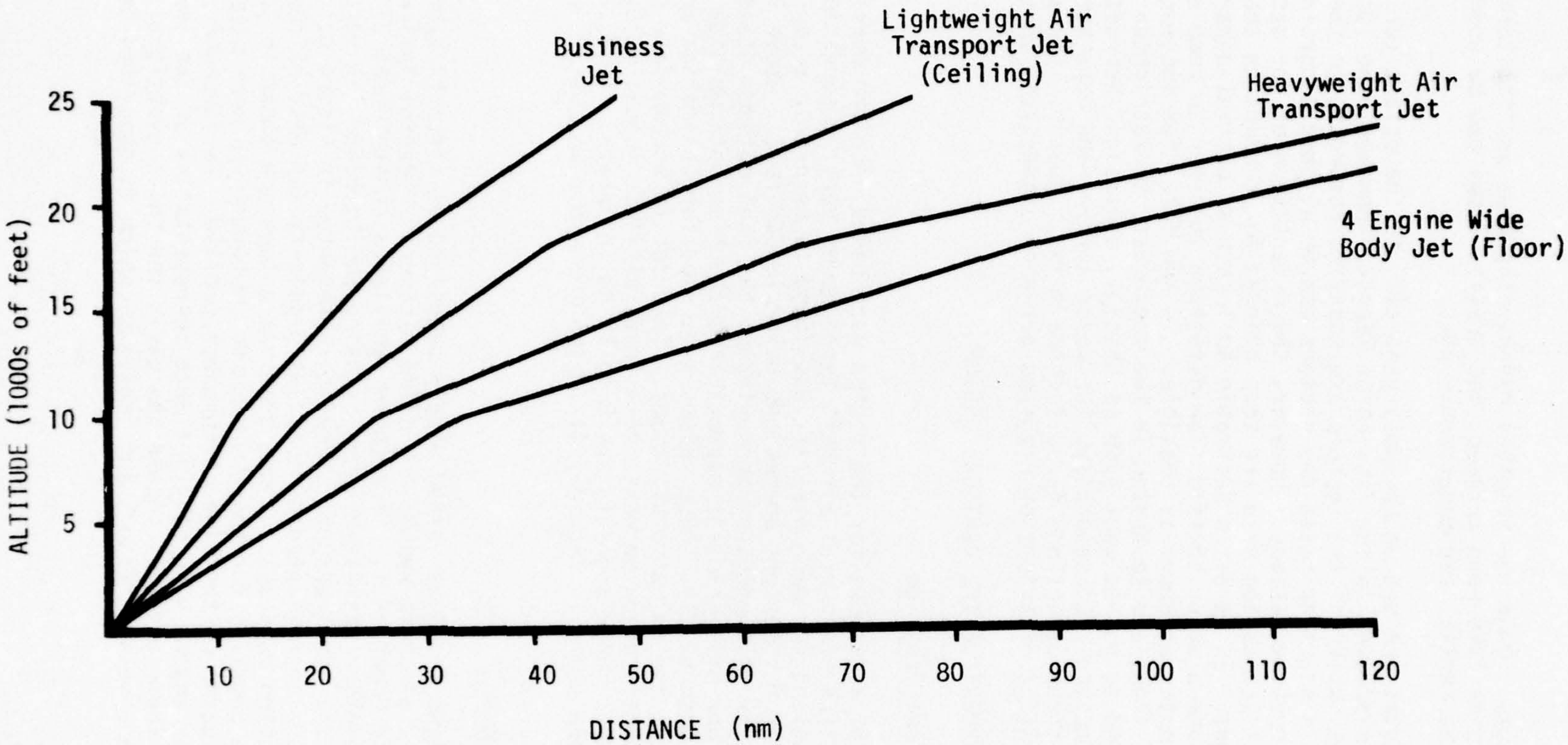


Figure 8.1 TYPICAL AIRCRAFT CLIMB PROFILES

Table 8.1 Climb Performance Profiles

Conventional Climb Performance Envelope			
Boundary Profile	Altitude	Gradient	Vertical Path Angle
Ceiling-Lightweight Air Transport Jet	0-10000 ft	550 ft/mile	5.2°
	10000-18000 ft	350 ft/mile	3.3°
	18000-25000 ft	200 ft/mile	1.9°
Floor-Four Engine Wide Body Jet	0-10000 ft	300 ft/mile	2.8°
	10000-18000 ft	150 ft/mile	1.4°
	18000-25000 ft	100 ft/mile	0.9°
High Performance Departure Envelope			
Boundary Profile	Altitude	Gradient	Vertical Path Angle
Ceiling - Business Jet	0-10000 ft	800 ft/mile	7.5°
	10000-18000 ft	500 ft/mile	4.7°
	18000-25000 ft	350 ft/mile	3.3°
Floor-Lightweight Air Transport Jet	0-10000 ft	550 ft/mile	5.2°
	10000-18000 ft	350 ft/mile	3.3°
	18000-25000 ft	200 ft/mile	1.9°

8.2.3 High Performance Departure Envelopes

Shortened routes or routes with fewer altitude restrictions are often possible for high performance aircraft. If an aircraft can achieve or exceed a specified vertical performance, it may often be cleared to the periphery of the terminal area via a shorter route because it will not interfere with traffic on conventional 2D RNAV routes. The use of a high performance departure envelope in these areas can provide a benefit to the user in terms of time and fuel conservation. These departure envelopes have gradients which are greater than those which define the conventional climb performance envelpe of Table 8.1. For designing high performance departure envelopes it was desirable to define intermediate and high performance profiles from which the vertical envelope dimensions could be determined. A high performance departure envelope would then be described as the region between the intermediate and the high performance profile. The intermediate performance profile is described by the lighweight air transport jet profile in Figure 8.1. The high performance profile is represented by the business jet profile in the same figure. These two profiles define the "floor" and "ceiling" of the high performance departure envelope whose gradients and vertical path angles are shown in Table 8.1.

In developing high performance departure envelopes it is desirable to provide separate high altitude departure waypoints and separate departure routes from the conventional performance routes. This was considered desirable

in order to avoid aircraft conflicts at the periphery of the terminal area. Normally the high performance routes are shorter than the conventional performance routes. Consequently a high performance aircraft following a conventional performance aircraft off the runway with adequate separation could later conflict if the two aircraft exited the terminal at the same point because the high performance aircraft climbed at a steeper gradient on a shorter route. This use of multiple departure points may have a significant impact upon the center sector that adjoins the terminal area.

8.2.4 Vertical Separation Criteria

All crossing route altitude restrictions should be based on accommodating both 2D and 3D equipped aircraft. The placement of altitude restriction points in accordance with 2D separation criteria will usually result in adequate 3D vertical separation as well, as discussed in Section 7.4.1 However, in some cases additional 3D vertical separation must be provided by moving the 2D altitude restriction point slightly. A comparison of 2D and 3D separation requirements is given in Appendix A.

8.2.5 Vertical Design of RNAV Routes

The vertical route design is accomplished by utilizing a vertical profile plot of altitude versus distance along track for each proposed route. Arrival routes are usually plotted first since their vertical envelope is less complicated than the desired vertical envelope for departure. Holding pattern airspace areas are identified on the profile plot for each arrival route. Route turn points and other significant operational points, such as feeder fixes, are identified as waypoints on the distance/altitude plot. Crossing route locations are then identified on the profile views of the two routes which form the route crossings. The desired climb gradient (the conventional climb performance envelope, Table 8.1) is used for the departure routes. For arrivals, a 300 ft/mile gradient is used as one vertical boundary while the other boundary is formed by a 400 ft/mile gradient followed by a 10 nm level deceleration segment at 10,000 ft followed by a 300 ft/mile gradient to sea level. These two boundaries cross at 22,000 ft. Above 22,000 ft the steeper gradient forms the route "ceiling". Below 22,000 ft the 300 ft/mile gradient forms the "ceiling". The arrival profiles were shown in Figure 7.41.

Altitude conflict situations are immediately recognized in the route profile views. The conflicts must be resolved by either imposing altitude restrictions or by moving the horizontal position of one or both routes.

An example of the vertical design procedure is shown in Figures 8.2-8.6. Figure 8.2 shows the horizontal view of the metroplex area. Route 200 is an RNAV arrival to airport X with waypoints 1, 2 and 3. Its profile view is shown in Figure 8.3. Route 300 is an RNAV departure from airport Z with waypoints 7, 8, 9 and 10. Its profile view is shown in Figure 8.4. Route 500 is a high performance departure route from airport Y using the performance profile discussed in Section 8.2.1. It has waypoints 4, 5 and 6 and its profile is shown in Figure 8.5. Routes 200 and 300 cross at

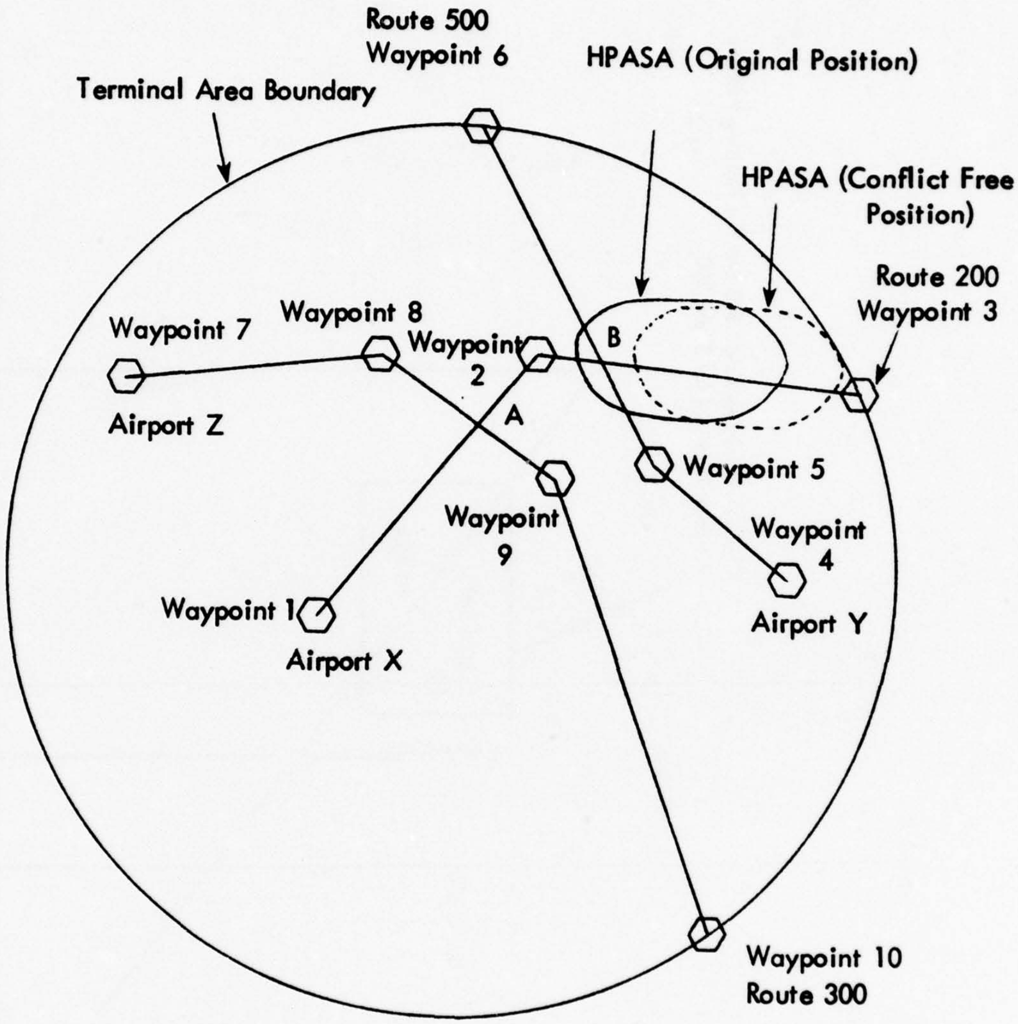


Figure 8.2 Example Horizontal Modified Task Force Terminal Design

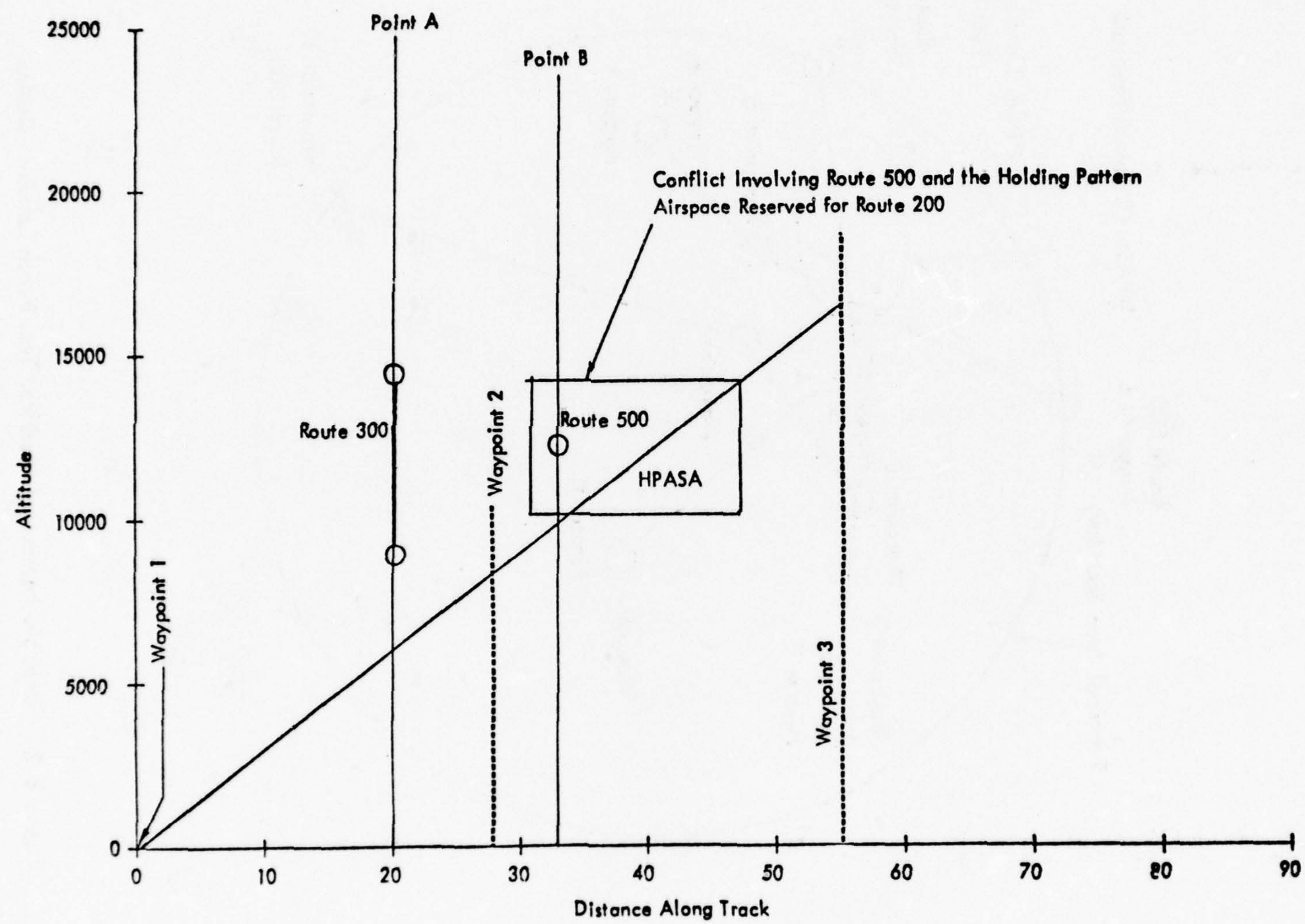


Figure 8.3 Route 200 Vertical Profile

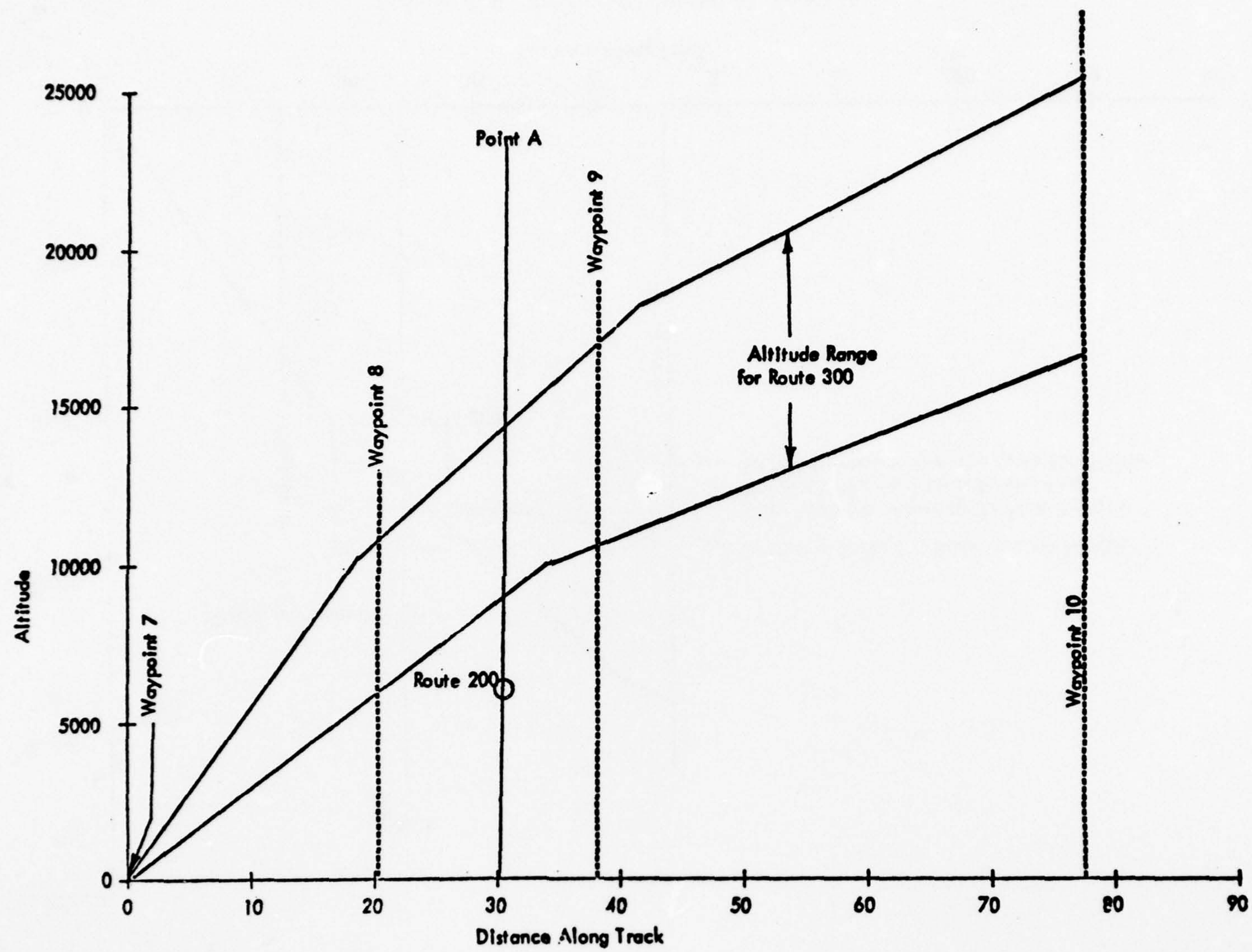


Figure 8.4 Route 300 Vertical Profile

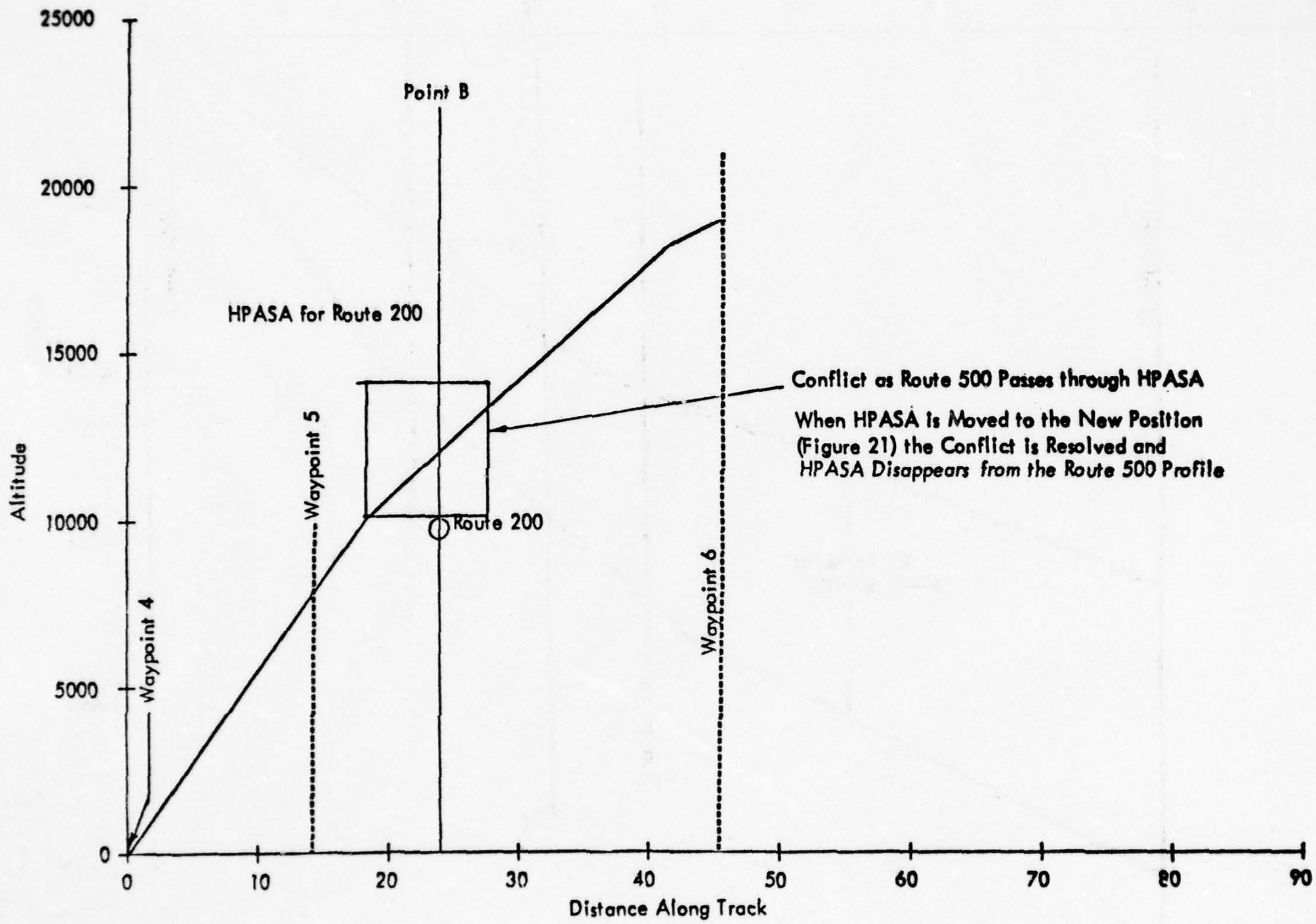


Figure 8.5 Route 500 Vertical Profile

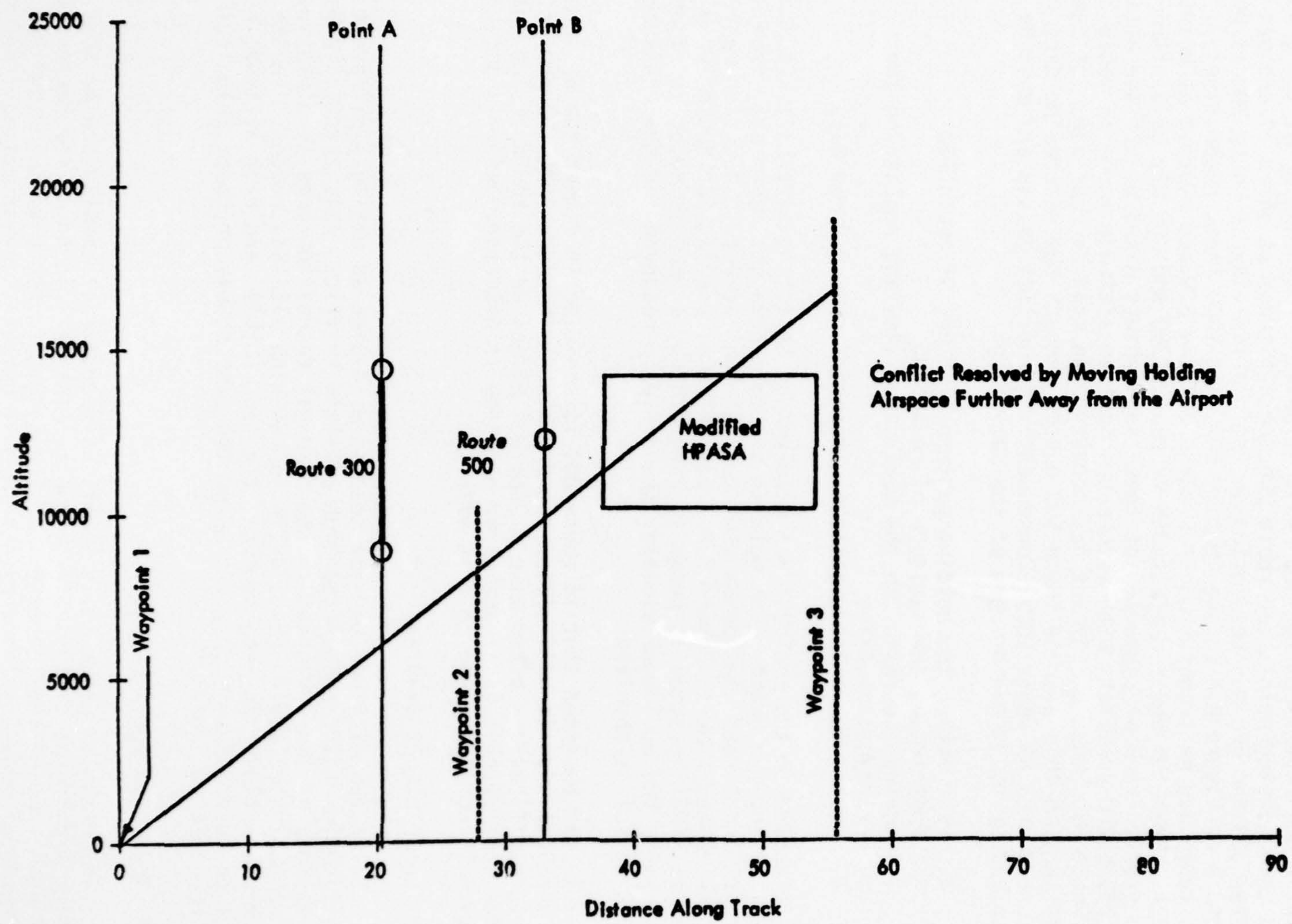


Figure 8.6 Route 200 Modified Vertical Profile

point A and routes 200 and 500 cross at point B. By looking at the gradient and the crossing points for route 200, the altitudes at which it crosses routes 300 and 500 may be plotted on the profile view of route 200 at points A and B on Figure 8.3 (approximately 6000 and 9000 feet, respectively). These altitudes may be transferred to Figures 8.4 and 8.5 and plotted at points A and B. Next the desired altitudes of routes 300 and 500 may be plotted on the profile view of route 200 at these same points A and B. If the altitude of route 200 conflicts with either the desired altitude range of route 300 or route 500, then a conflict has occurred and must be resolved. It can be seen that in this example route 500 passes through the desired holding pattern airspace area of route 200. Consequently a conflict exists and must be resolved by doing one or more of the following:

1. restricting the holding pattern altitude of route 200
2. restricting the latitude of route 500
3. moving the routes in the horizontal view and replotting the vertical profiles
4. moving the holding pattern airspace (Figure 8.2 and 8.6)

In this example the conflict was resolved by selecting alternative number four, moving the HPASA. The holding airspace area was moved away from the airport and toward the boundary of the terminal area to a position represented by the dashed line in Figure 8.2. The vertical profile for Route 200 with the new HPASA location is shown in Figure 8.6. It can be noted in Figure 8.6 that Route 500 no longer violates the airspace reserved for the HPASA and thus the conflict is resolved.

It can be noted that if route 200 is modified in either the horizontal or vertical view it will affect the crossing with route 300. Consequently, route modifications often have a "domino" effect on the route design analysis. Often considerable trial and error plotting is necessary before a satisfactory design is completed due to this effect.

8.3 Low Altitude Traffic

Often low altitude non-jet traffic will have an entirely different traffic distribution pattern than the high altitude traffic. This traffic is permitted to operate at low altitudes in the terminal transition area in directions and on routes which may go cross-grain to the high altitude routes. In the terminal maneuvering area however, the low altitude and high altitude routes must be coincident if they are using the same runway or compatible if they are using different runways.

8.4 Metroplex Applications

In metroplex areas it is sometimes necessary to modify one or more of the design procedures discussed previously. The definition of the center of the terminal complex and the extent of the terminal area have to be defined by operational considerations rather than by geometric descriptions. For example, in the New York terminal area a 47 nm circle centered approximately 2 nm west of La Guardia was used. This terminal boundary was selected because these dimensions encompassed the present feeder fixes in the New York area and because the 47 nm circle was an approximate representation of the jurisdiction

of the New York Common IFR Room. Other dimensions would be required for different metroplex areas. The Task Force recommended technique of constructing 45 nm circles about each airport and then drawing one large circle about the smaller circles was not used, because using this technique in an area such as the Northeast Corridor would create one very large circle around the whole northeast coastal area if it were applied literally. Consequently, basing the terminal size on operational considerations such as the location of feeder fixes and TRACON size was considered to be a superior technique.

In a metroplex area routes to the major airports will often conflict if the flow patterns to the various airports are not carefully designed. In high density arrival areas, independent parallel routes are used wherever possible in order to facilitate traffic flow and make maximum use of the available airspace. Arrivals converge at the feeder fix which is the low altitude arrival waypoint and traffic is assumed to flow in trail from the feeder fix to the runway. Arrivals in low density arrival areas may share arrival routes and feeder fixes in order to achieve a higher degree of airspace utilization.

Departures from the metroplex airports may share routes to a greater extent than the arrivals. Due to the fact that departures are increasing their speed as they exit the terminal area, there are generally less congestion problems associated with departures than arrivals. However, airspace should be provided to permit the use of a parallel offset in case congestion or overtake situations should arise. The question of when to use a single arrival or departure route for airports in the terminal area and when to use multiple routes is not one that is easily answered. There are interacting considerations of traffic density, control jurisdiction and airspace availability. Ultimately, the final terminal design should be based upon the type of structure which best suits the composite requirements of the terminal area airspace, the enroute traffic management considerations, the controllers and the users.

In the terminal manuevering area the constraints of the metroplex area often force operations to one side of an airport. This is readily apparent in the design for New York (Figure 8.7). The Kennedy operations are confined to the eastern side of the airport, Newark operations are kept to the west side of the airport and La Guardia operations are forced into a narrow corridor along each side of the airport. Departing traffic is turned toward the enroute departure fix as soon as they are clear of other traffic. Once the horizontal design of the metroplex area has been established, the vertical design of the routes proceeds as described in Section 8.2. Routes to all major airports must be considered in the vertical route design.

8.5 APPLICATIONS TO OTHER TIME PERIODS

While the RNAV Task Force Report calls for the implementaion of RNAV terminal area route structures in three time periods, the modified terminal area design guidelines provide for an evolutionary transition from VOR/radar vector route structures to RNAV route structures. The modified design guidelines provide for the identification of terminal area waypoint locations from

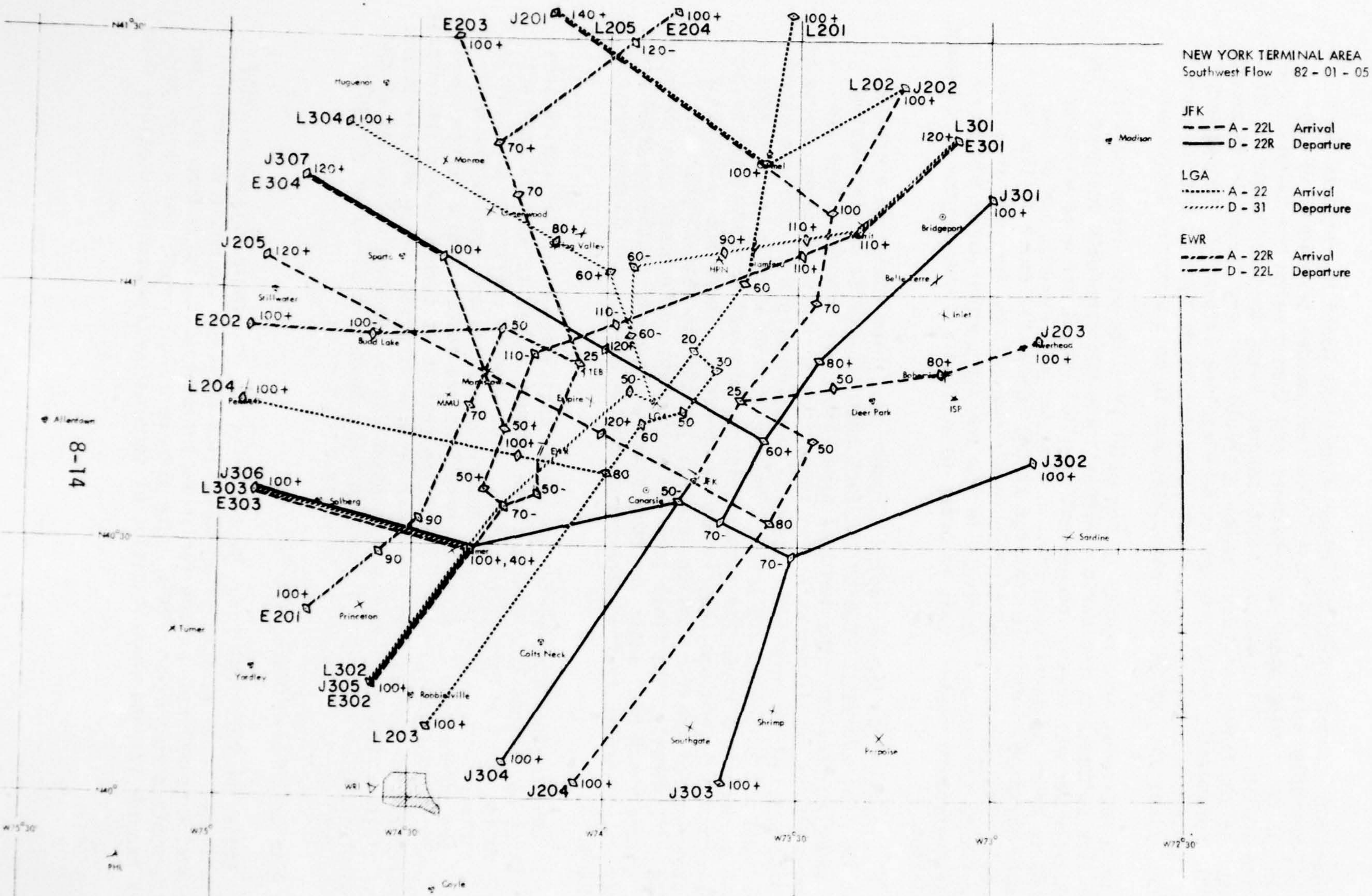


Figure 8.7 Final 1982 New York Terminal Area Design (without High Performance Routes)

enroute traffic flow data. Several combinations of arrival and departure sectors and the number of waypoints per sector can be used in the waypoint selection process. The final choice of the waypoint locations is based upon a combination of user benefit and ATC considerations. From a user benefits standpoint the waypoint locations which provide the most direct access to the arrival or destination city is desired. From an ATC standpoint, RNAV can be implemented quite readily in the terminal area if these routes are fairly well aligned to the existing traffic flows in the terminal area. In the seven terminal areas that were analyzed during this study, it was possible in all cases to satisfy both a user benefit requirement and the ATC implementation requirement and arrive at terminal waypoint locations which were satisfactory from both points of view. These terminal areas represent a diverse set of terminal area characteristics in medium and high density areas. Consequently, it is believed that these design procedures could produce equally satisfactory terminal route structures in other high and medium density terminal areas. The design procedures that should be used in producing these new route structures consist of the following steps:

Step 1. First, the existing VOR/radar vector route structure must be identified. This consists of identifying Victor and Jet routes which are used by arriving and departing traffic in the terminal area. In addition, any other radar routes which are used should be identified as well. In addition, the important fixes, feeder fixes and holding fixes should be identified. Next, the terminal maneuvering area route structures for the primary runway configurations must be identified.

Step 2. The second step of the terminal design process is the development of candidate terminal waypoint locations based on enroute traffic flow. Comprehensive traffic samples must be used in order to perform this task. Scheduled air carrier and air taxi operations may be taken from Official Airline Guide data such as Reference 15. General aviation traffic data is somewhat more difficult to determine accurately, however, the origin or destination and type of aircraft that are used by general aviation should be included as well. Once a traffic sample has been obtained, a waypoint optimization program such as that described in Section 7.5.1 can be used to determine candidate terminal waypoint locations.

Step 3. The existing route structures that were determined in Step 1 and the candidate terminal area waypoint locations that were found in Step 2 are now compared and as a general rule the candidate waypoint location which most closely aligns itself with the existing traffic flow is then selected as a basis from which to develop the final RNAV route structure. Terminal area route structures are then developed for the runway configurations that are generally used in the terminal area. Careful attention should be given to the vertical profile of each route. The vertical design techniques that were described in Section 8.2 should be employed in all crossing route situations. This design procedure provides for a minimum user penalty insofar as excessive altitude restrictions are concerned.

Step 4. When the designs for the primary runway configurations are completed, a route length and altitude restriction analysis should be performed in which the RNAV route structure is compared with the VOR/radar vector route structure that was developed in Step 1. This analysis will point out any weaknesses in the RNAV route structure which would adversely affect user benefits. A final adjustment of the RNAV route structure is then made based on the user benefits analysis. At this point there now exists a terminal area route structure which was designed specifically for RNAV equipped aircraft only and a VOR/radar vector route structure which can be flown by aircraft without RNAV equipment.

As users become equipped with RNAV, the demand for terminal RNAV routes will increase. Those routes for which there is sufficient demand can be implemented according to the RNAV route structure that was developed in Step 4. The implementation of routes for which there is little RNAV demand may be postponed until such time as the user demand warrants.
This design technique provides for an orderly step-by-step implementation of RNAV into the terminal area. This procedure also insures that there is a well-planned terminal design goal which will provide economic advantages to the user with a minimum impact upon the terminal ATC operators.

This design procedure can be adapted to a unified RNAV route structure development for the entire U.S. The terminal route design technique that was described in the proceeding paragraphs serves to identify the enroute connecting points for each terminal area for which such a design procedure is performed. Through the use of transition area and enroute area RNAV route design guidelines it is possible to construct an enroute RNAV structure which will show the same characteristics of user benefits combined with minimum ATC impact. The results of such a program would provide a master plan for the implementation of RNAV routes in all areas of the country. The use of this plan for RNAV implementation would provide for an evolutionary transition from a present VOR/radar vector environment to an airspace structure based upon the use of area navigation.

9.0 CONCLUSIONS

The conclusions presented in this section are based upon all of the designs that were developed during the course of the study. These designs include the initial design efforts which were based upon a strict interpretation of the RNAV Task Force terminal area design guidelines for RNAV and VNAV routes, and on the second design effort in which the route structures were based upon the modified terminal area design guidelines. The initial design effort included the time-phased designs (1972-77, 1977-82, post-1982) for seven terminal areas (13 airports) and fixed gradient VNAV designs for New York and New Orleans. The second design effort included the development of the amended 1972 RNAV routes for the seven terminal areas, the post-1982 New York modified design which made use of high performance departure routes, and the final 1982 RNAV routes for the seven terminal areas. All of the final 1982 designs were based on the vertical envelope concept for both arrival and departure aircraft. The high performance departure envelope concept was utilized only in the New York terminal area. In addition some conclusions are based upon the real time simulations of the 1972 and 1977 New York designs, which were developed in the initial design effort, and the post-1982 New York modified design, which was developed in the second design effort. The conclusions are based on terminal area factors only, including consideration of enroute traffic flow, and may be modified in some cases by the specific details of the enroute/transition interface.

RNAV TERMINAL AREA DESIGN PRINCIPLES

1. The application of the basic design should incorporate consideration of traffic distribution demand as well as runway orientation constraints. Similarly, the number and size of alternating departure and arrival sectors should be varied as necessary to accommodate traffic demand, rather than being constrained to equal size octants. The size and orientation of the sectors should be based upon a consideration of both the direction of traffic and the level of traffic in each direction. The designs will thus be optimized for aggregate user benefit. In metroplex areas additional constraints of conflict minimization must be imposed upon the design which will impact the sector size and orientation. The orientation of the octant design, as postulated by the Task Force, is based upon the location of the primary IFR arrival runway and the size of the octants is fixed. These constraints sometimes will produce a design which creates a longer flight path distance to the runway than would a design which is based upon traffic distribution in all directions from the airport. The recommended guidelines allow orientation and sizing of the terminal transition area to be assigned according to traffic distribution.

2. In metroplex areas the number and size of the alternating arrival and departure sectors may differ from the Task Force concept even more drastically in order to provide parallel traffic corridors or merged routes which minimize undesirable altitude restrictions and excessive route lengths.

3. The location of low altitude arrival waypoints in the Task Force RNAV terminal area design model (25 nm from the airport) is in general agreement with the location of current radar vector/VOR feeder fixes at most airports. The use of the low altitude arrival waypoint may be eliminated in some circumstances. If that point has an operational use such as a handoff point

or a holding fix then it should be retained, however, in a low traffic density situation or an automated metering and spacing environment, aircraft may skip the low altitude arrival waypoint and proceed from the terminal boundary to the downwind or base leg turn waypoint if a shorter flight path is achieved.

4. The use of the low altitude departure waypoint should be eliminated where possible. Instead, aircraft should depart the terminal area by climbing to a maneuvering altitude and turn toward the direction of the appropriate departure area. From this point departures should proceed directly to the terminal area boundary waypoint. Additional departure waypoints should be used only for conflict avoidance or altitude restrictions.

5. The downwind, base and final approach leg used in the Task Force design within 25 nm of the airport is consistent with current airport traffic patterns for all seven terminal areas analyzed to date. This procedure should be retained in all RNAV design considerations. If an operational advantage can be gained by eliminating or modifying the downwind, or downwind and base legs of an approach, then these route segments should be deleted. The long straight-in approach at Denver from Byers Intersection to Runway 26 in the 1972 design and the modified 1982 design is an example of this type of advantage.

6. The low altitude traffic did not need to be constrained by the octant concept. In most of the terminal designs, it was possible for departing low altitude traffic to proceed direct to their enroute waypoints once they passed beyond the terminal manuevering area. Similarly, arrivals could proceed from their point of origin to the low altitude arrival fix without interfering with high altitude traffic flow. An exception was experienced in New York however. In New York both the low and high altitude traffic were constrained to the same flow pattern out to 47 nm so that low altitude traffic would not conflict with arrivals and departures at other airports.

7. The use of a 45 nm circle centered at the primary airport is a satisfactory conceptual aid in defining the extent of a non-metroplex terminal area. The 45 nm circle does not necessarily have any operational significance however. Consequently, in actual terminal area design operational considerations concerning the location of terminal enroute boundaries should take precedence over the use of the conceptual 45 nm boundary.

8. The concept of defining the metroplex terminal area by encircling each airport with a 45 nm ring and then encircling all the 45 nm rings with one large ring, as recommended by the Task Force, is not feasible in congested regions such as the Northeast Corridor. It is necessary in these metroplex areas to limit the extent of the terminal area by considering the location of all major airports within the metroplex and the proximity of adjacent terminal areas. A circle of 47 nm radius which was centered 2 nm west of La Guardia was used at New York. This radius and location was selected because it encloses all of the currently used feeder fix locations in the New York terminal area.

9. Lateral route dimensions of ± 2.0 nm will accommodate the RNAV route structures and provide maneuvering airspace in the final terminal area designs which were developed. Maneuvering airspace will be required in all designs in the vicinity of the final approach course for use by the controller for aircraft separation. The ± 1.5 nm route width as suggested by the RNAV Task Force for the 1977 and 1982 time periods was not necessary to accommodate the modified 1982 RNAV route structures for any of the seven terminal areas covered by the study.

10. Vertical envelopes should be used for both arrival and departure traffic. For arrival aircraft a single vertical descent gradient of 300 ft/mile is achievable for aircraft from any altitude. However, a descent gradient of 400 ft/mile down to 10,000 ft. followed by a level deceleration segment of up to 10 nm and finally a descent gradient of 300 ft/mile below 10,000 ft. can be beneficial for high performance aircraft making high speed descents.

The vertical envelope for departure aircraft is based upon a wide range of aircraft performance. The following gradient values were used:

Altitude	Gradient
0 - 10000 ft.	300 - 550 ft/mile
10000 - 18000 ft.	150 - 350 ft/mile
18000 - 25000 ft.	100 - 200 ft/mile

High performance departure routes should be used when shorter departure distances and/or fewer altitude restrictions can be obtained. These routes are limited to aircraft which are capable of exceeding the following gradient values:

Altitude	Gradient
0 - 10000 ft	400 ft/mile
10000 - 18000 ft	200 ft/mile
18000 - 25000 ft	100 ft/mile

These gradient values thus form the "floor" of the high performance departure envelope.

1972-1977 TERMINAL DESIGNS

11. Most terminal areas are currently structured in a wagon wheel or spoke type flow pattern with fixed arrival and departure points. However, most spokes are not of equal size nor are they spaced in an octant pattern. In the 1972-77 time period all RNAV routes within the terminal maneuvering area (inside of the arrival and departure fixes) should overlie the basic radar vector routes. Outside of the terminal maneuvering area, RNAV routes should be established in areas where user benefits will accrue. User benefits include shorter route lengths, a minimum of restrictions during climb and descent, and better alignment with the traffic flow.

12. The results of the real time simulation of the 1972-1977 New York route structure indicate that, contrary to the concerns expressed by the Task Force, there was no evidence of a negative impact on controller workload in a mixed VOR/RNAV terminal area environment and, in fact, substantial reductions in

controller workload were observed as the percentage of RNAV traffic increased. In addition, this specific simulation produced no evidence of any reduction in terminal area capacity as the percentage of RNAV aircraft was increased.

13. The use of the modified terminal area design guidelines can produce RNAV terminal area route structures that are often very compatible with existing VOR/radar vector route structures. Consequently, RNAV routes that are compatible with existing route structures can be implemented as soon as a user requirement exists, thus providing for user benefits in this initial RNAV implementation time period.

1977-1982 TERMINAL DESIGNS

14. The 1977-1982 terminal designs must be able to accommodate both conventional radar vector/VOR and RNAV traffic. This represents a considerable constraint upon the design. The flow patterns for this transitional time period should be based upon the post-1982 terminal design, which should of itself be created prior to the development of the 1977-1982 design. The location of feeder fixes and departure fixes should be near those created in the post-1982 design but moved as necessary to accommodate VOR traffic. Traffic in the terminal maneuvering area should generally conform to the post-1982 design.

15. As in the 1972-77 transition period, the mixed VOR/RNAV environment of the 1977-72 transition period will provide substantial reductions in controller workload with no negative impact upon terminal area capacity.

16. As independent terminal RNAV routes are added, based on post-1982 designs, user economic benefits will continue to accrue.

POST-1982 TERMINAL DESIGNS

17. The concept of using arrival and departure sectors in designing terminal area routes should be used for most medium and all high density terminal areas. The size and orientation of these sectors should be based primarily on the direction and density of traffic flow. A rigid specification of the location, size and orientation of the sectors such as the octant concept suggested by the RNAV Task Force, can create operational penalties such as increased distance flown and additional altitude restrictions in complex terminal areas. The modified terminal route design concept developed in this study is designed to avoid these penalties.

18. In metroplex areas, arrival and departure fixes should be located on the basis of optimum enroute traffic flows and compatible terminal area routes from the major airports. Traffic should proceed to a conventional downwind, base and final approach sequence in the most direct manner possible without interference from adjacent terminal routes. Altitude restrictions should be determined from typical aircraft altitude vs. along track distance profiles.

19. The results of the real time simulation of the post-1982 New York route structure indicate that controller workload decreased as the percentage of RNAV and VNAV equipped aircraft operating in the terminal area increased. These workload reductions continued to be observed when the operation rates were at full capacity levels. The terminal arrival capacity, measured in terms of arrivals per hour, increased as the percentage of area navigation aircraft increased. An average arrival capacity increase of 3% was observed for the all RNAV/VNAV equipped cases versus the radar vector case, based on statistical regression analyses. No significant change in departure capacity was noted as the percentage of equipped aircraft increased.

20. The results of the real time simulations of New York Kennedy for all three time periods indicate that the use of RNAV procedures are more responsible for controller workload reduction than are the specific characteristics of the RNAV route structure. This observation is probably true in terms of arrival capacity increases, also. Thus controller workload reductions and arrival capacity increases can be expected in terminal area operations as RNAV aircraft and the use of RNAV control procedures are increased with or without changes in the terminal area route structure.

21. The use of arrival and departure envelopes provides airspace utilization approximately equivalent to constant gradient VNAV routes with the advantage of a significant user benefit through the use of pilot-selected vertical profiles as opposed to the user penalty associated with fixed gradient VNAV routes.

22. The fixed gradient VNAV design concept would produce an inflexible route structure from an ATC standpoint which would make the use of impromptu, ATC requested maneuvers difficult, if not impossible, in congested terminal areas.

23. The arrival route design technique which employs the vertical envelope concept can provide optimum user benefits for both VNAV and RNAV users. Utilizing the routes produced by this design procedure allows the user to select a fuel optimum descent, a time-optimum descent, or some intermediate descent schedule when there is sufficient airspace available.

24. The use of high performance departure envelopes, whose minimum gradient is higher than the normal departure envelopes, can provide additional benefits to higher performance aircraft through shorter departure route distances and/or fewer altitude restrictions.

25. A team of field controllers could find no apparent ATC benefits when fixed gradient or stacked VNAV routes are used in terminal areas. In particular, the controller team was concerned about complex crossing altitude considerations when aircraft must be taken off of the primary VNAV route for any reason.

REFERENCES

1. "Application of Area Navigation in the National Airspace System," FAA/Industry RNAV Task Force Report, February 1973.

2. A.G. Halverson, et al, "Area Navigation High Altitude Network Study," Report No. FAA-RD-76-6, National Aviation Facilities Experimental Center of the Federal Aviation Administration, Atlantic City, New Jersey, February 1976.

3. E.H. Bolz, et al, "Economic Impact of Area Navigation," Report No. FAA-RD-75-20,I, Systems Control, Inc./Champlain Technology Industries, West Palm Beach, Florida, prepared for the Systems Research and Development Service of the Federal Aviation Administration, August 1975.

4. "Airline Proposed Applications of Area Navigation in the ATC System," Working Paper, Air Transport Association, December 1971.

5. "Minimum Operational Characteristics - Vertical Guidance Equipment Used in Airborne Volumetric Navigation Systems," Document DO-152, RTCA SC116E.

6. "DC-8 Model 63 General Performance Report," McDonnell Douglas Corp., Revised June 1971.

7. "DC-9 Series 30 General Performance Report," McDonnell Douglas Corp. Revised June 1971.

8. "DC-10 Series 10 General Performance Report", McDonnell Douglas Corp., November 1972.

9. "Enroute IFR Air Traffic Survey - Peak Day Fiscal Year 1971", Department of Transportation, Federal Aviation Administration, March 1972.

10. "Airman's Information Manual," Federal Aviation Administration.

11. Manufacturers Aircraft Performance Report, Boeing Company, Airplane Division, Renton, Washington - Model 727, JT8D-7 Engines, Report D6-6444-1, August 1965.

12. Manufacturers Aircraft Performance Report, Boeing Company, Airplane Division, Renton, Washington - Model 747B, C and F, JT9D-7 Engines, Report D6-30187, October 1968.

13. J. Maurer, et al., "Preliminary Two Dimensional Area Navigation Terminal Simulation", Report No. FAA-RD-74-209, National Aviation Facilities Experimental Center of the Federal Aviation Administration, Altantic City, New Jersey, February 1975.

14. E. H. Bolz, "Preliminary Analysis of Impact of RNAV on ATC Economics", Unpublished Draft Report, Systems Control, Inc./Champlain Technology Ind., West Palm Beach, Florida, prepared for the Systems Research and Development Service of the Federal Aviation Administration, March 1973.

15. Official Airline Guide, North American Edition, Reuben H. Donnelley Publication, Oak Brook, Illinois, December 1, 1974.

16. W.H. Clark, et al., "Implementation of Area Navigation in the National Airspace System: An Assessment of RNAV Task Force Concepts and Payoffs", Report No. FAA-RD-76-196, Champlain Technology Industries, Division of Systems Control, Inc. (Vt), West Palm Beach, Florida, prepared for the Systems Research and Development Service of the Federal Aviation Administration, September, 1976.

17. R.J. Adams, "An Operational Evaluation of Flight Technical Error", Report No. FAA-RD-76-33, Champlain Technology Industries, Division of Systems Control, Inc. (Vt), West Palm Beach, Florida, prepared for the Systems Research and Development Service of the Federal Aviation Administration, September, 1976.

18. W. Crimbring and J. Maurer, "Area Navigation/Vertical Area Navigation Terminal Simulation", Report No. FAA-RD-76-28, National Aviation Facilities Experimental Center of the Federal Aviation Administration, Atlantic City, New Jersey, April 1976.

19. R.J. Adams, "Area Navigation Waypoint Designation Standards", Report No. FAA-RD-75-122, Champlain Technology Industries, Division of Systems Control, Inc. (Vt), West Palm Beach, Florida, prepared for the Systems Research and Development Service of the Federal Aviation Administration, August 1975.

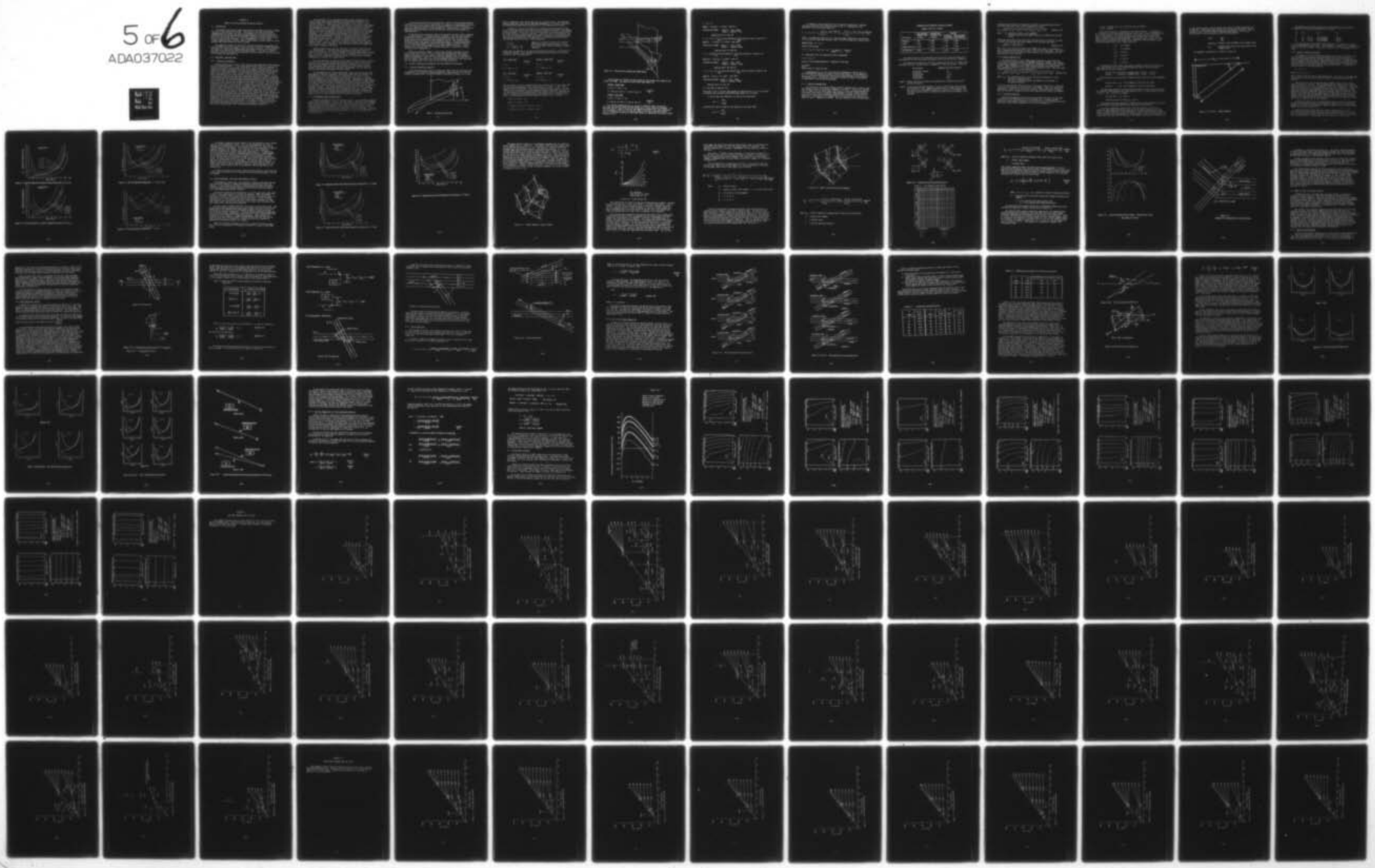
20. R.J. Adams, "Preliminary RNAV Avionics Standards (2D and 3D Area Navigation Systems)", Report No. FAA-RD-75-178, Champlain Technology Industries, Division of Systems Control, Inc. (Vt), West Palm Beach, Florida, prepared for the Systems Research and Development Service of the Federal Aviation Administration, November, 1975.

21. R. Pursel and J. Edmonds, "A Flight Investigation of System Accuracies and Operational Capabilities of an Air Transport Area Navigation System", Report No. FAA-RD-76-32, National Aviation Facilities Experimental Center of the Federal Aviation Administration, Atlantic City, New Jersey, May, 1976.

AD-A037 022 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
TERMINAL AREA DESIGN - ANALYSIS AND VALIDATION OF RNAV TASK FOR--ETC(U)
OCT 75 E D MCCONKEY , W H CLARK DOT-FA72WA-3098

UNCLASSIFIED FAA-RD-76-194 NL

5 OF 6
ADA037022



5 OF 6

ADA037022

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

APPENDIX A

IMPACT OF VNAV ON AIRSPACE DESIGN AND CAPACITY

A.1 INTRODUCTION

The terminal area design concept envisioned by the RNAV Task Force included the use of fixed gradient 3D routes. The terminal area design guidelines recommended by this report are based on widespread use of pilot-selected 3D gradients within climb and descent envelopes defined by altitude restrictions, but do not include the use of fixed vertical gradients to define routes as part of the airspace design procedure. This recommendation is based on user economic considerations, airspace capacity requirements, and the impact of fixed gradient VNAV route designs on the ATC system.

This Appendix presents an analysis of vertical separation requirements for crossing VNAV routes, the impact of turns and parallel offsets on VNAV separation, the impact of fixed gradient VNAV routes on airspace capacity, and along track and cross track accuracy of VORTAC-based VNAV systems. The impact of VNAV on controller and pilot procedures and workload is also discussed. Sections A.4 and A.5 are taken from Reference 16.

A.2 PROCEDURAL CONSIDERATIONS

A.2.1 Controller Procedures

A major problem area in which little work has been published to date concerns controller VNAV procedures. It is quite apparent from looking at a New York 3D terminal area design, as conceived in Section 7, that current sectorization schemes and control procedures would have to be amended in order to work in this type of 3D airspace environment. At the present time controllers have responsibility for areas which are well defined in the horizontal plane by lines on their video display, and in the vertical plane by specified altitudes. In the fixed-gradient 3D route terminal area design the airspace is organized according to the fixed gradient routes and their associated protected airspace around the route centerline. An aircraft following a 3D route has both his lateral position and altitude specified by the parameters which define the route. The only degree of freedom that the aircraft has in which its position is not controlled is the position along the route. This position is, however, determined by the speed of the aircraft, thus this position also is relatively fixed. This means that at any point in time an aircraft on a fixed gradient VNAV route has its position fairly well predetermined. In order for the controller to exert any sort of control on the position of that aircraft he must have the flexibility to take the aircraft off of the prescribed VNAV route in either the vertical or horizontal direction. Without this flexibility the controller can do very little more than monitor the progress of the aircraft along the fixed gradient flight path. In such instances, separation could be achieved through the use of speed commands only and the result would be a very regulated airspace. This type of airspace design would not provide any degree of flexibility for the controller to efficiently mix aircraft of varying speeds and climb/descent performance capability.

The alternative to the regimented airspace design imposed by the fixed gradient VNAV routes described in the preceding paragraphs is to provide airspace for maneuvering aircraft either in the lateral or the vertical direction. This operational flexibility is achieved at the present time through the use of blocked airspace to permit the mixing of high and low performance aircraft through the use of altitude separation and/or vectors in a radar environment. Similar flexible maneuvers can be obtained through the use of 2D RNAV plus the parallel offset capability of the RNAV equipment. In a fixed gradient 3D environment such maneuvers could be accomplished through parallel offsets or possibly along track offsets to adjust the vertical profile. In order to accommodate these 3D procedures, additional airspace must be allocated to the basic protected airspace around the route. This, in essence, is blocked airspace around the fixed gradient route. Thus, the use of fixed gradient 3D routes would appear to have little to offer in the way of more efficient terminal area operations or efficient airspace utilization.

Another problem that faces the controller is conflict identification in a 3D environment. Currently the most advanced technology displays in operation are the ARTS III videos with Mode C providing alphanumeric altitude data. Certainly a serious question exists as to whether such a display is adequate for the controller to identify conflict situations and off-route excursions in a complex 3D airspace design.

It may be necessary to display to the controller the aircraft's vertical profile as well as its horizontal path on the video display in order for a controller to adequately monitor the aircraft's progress along its route. This requirement would nessitate the development of new display hardware, software and perhaps additional input data requirements for the controller such as waypoints and altitudes for each aircraft.

The implementation of fixed gradient VNAV routes would necessitate the development of new ATC procedures. According to the Task Force Report only selected areas of the airspace would be organized on the basis of fixed gradient 3D routes. The remainder of the terminal areas would be designed to have 2D RNAV routes with altitude restrictions. Consequently, there would exist an interface area where there would be a transition from 3D RNAV control to 2D RNAV control of aircraft in which new control procedures would have to be developed. Complicating the situation further, there would be the impact of equipment outages. Such situations include loss of the ATC radar, ground computer, airborne transponder, aircraft communications, etc. Each of these situations would have to be carefully analyzed and procedures developed so that the ATC system could handle these contingency situations as they arise before the use of fixed gradient 3D routes could be considered.

A.2.2 Pilotage/Workload Considerations

Several considerations arise for the pilot who is using 3D RNAV procedures rather than 2D procedures. First of all, the pilot is now required to maintain vertical flight path control during all flight phases rather than just during level segments and final approach. This control procedure creates a much different spatial climb profile than conventional control techniques. This in turn means that the pilot must fly the aircraft in a different manner utilizing a combination of pitch trim and throttle control to stay on the specified vertical gradient.

The specified profile must be maintained in spite of adverse meteorological conditions such as tail winds, head winds, wind shears, and temperature variations. Such conditions would produce widely varying conventional flight indications such as airspeed and rates of climb and descent. These changes in flight profile techniques may necessitate pilot proficiency and retraining requirements for VNAV operations.

Flying VNAV profiles requires inputs for waypoint altitudes and/or gradients for each path segment. The combination of data entry tasks and more stringent flight path control requirements can produce additional work for the pilot. During terminal area operations where waypoints may be close together these additional tasks could create a pilot workload problem. The workload problem can be alleviated somewhat by requiring multiple waypoint storage capacity or by utilizing flight data storage units and VNAV coupled autopilots. Flight technical error during VNAV final approach operations is discussed in detail in Section 3.8 of Reference 17.

There are instances, however, in which the automatic equipment can be a burden rather than an aid. This can occur when the equipment experiences a temporary outage or when ATC issues a clearance amendment and the equipment must be reprogrammed. These ATC interface type problems bring up questions of both the type of information that can be exchanged between pilot and controller and the language that can be used to describe these procedures.

A.3 VERTICAL SEPARATION REQUIREMENTS FOR FIXED GRADIENT VNAV ROUTES

A.3.1 Vertical Separation Equation

The protected airspace about a 3-dimensional RNAV route has been described in Appendix C of RTCA-DO150, "Minimum Operational Characteristics for Vertical Guidance Equipment Used in Airborne Volumetric Navigation Systems", as a tube

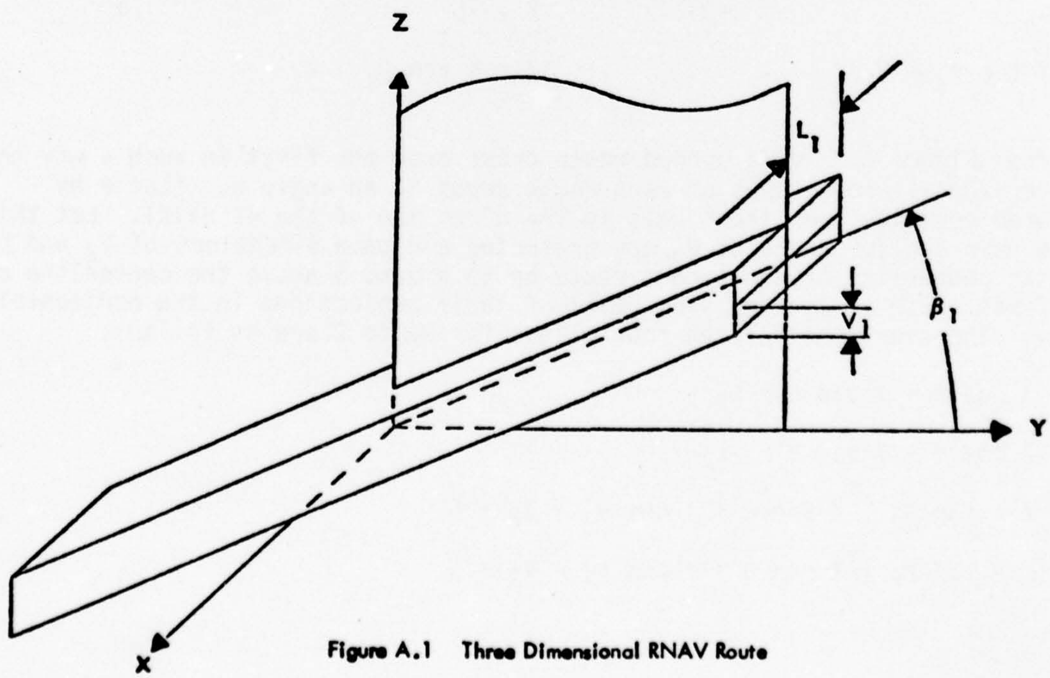


Figure A.1 Three Dimensional RNAV Route

with a rectangular cross section when cut by a vertical plane. The protected airspace about each route can be described mathematically in terms of two pairs of intersecting planes which are parallel to a line describing the route.

In Figure A.1 locate the origin of a cartesian coordinate system at some point on the centerline of a 3D route that is aligned at an angle β_1 with respect to the horizontal. Align the Y axis in the horizontal plane along the direction of flight assuming a climbing trajectory. Align the Z axis to the vertical and the X axis in the horizontal plane in a manner to complete a right handed triad. The protected airspace about this centerline can be described by four planes that are parallel to the route. These planes are:

$$X = L_1$$
$$X = -L_1$$
$$Z = Y \tan \beta_1 + V_1$$
$$Z = Y \tan \beta_1 - V_1$$

where V_1 is one half of the total vertical protected airspace dimension and L_1 is one half of the total lateral protected airspace dimension.

Assume that the observer is on the route centerline looking in the direction of increasing altitude. Then the edges of the protected airspace are the intersections of the following planes:

<u>Top - Right Edge</u> — Equation (1)

$$X = L_1$$
$$Z = Y \tan \beta_1 + V_1$$

<u>Bottom - Right Edge</u> — Equation (2)

$$X = L_1$$
$$Z = Y \tan \beta_1 - V_1$$

<u>Top - Left Edge</u> — Equation (3)

$$X = -L_1$$
$$Z = Y \tan \beta_1 + V_1$$

<u>Bottom - Left Edge</u> — Equation (4)

$$X - -L_1$$
$$Z = Y \tan \beta_1 - V_1$$

Now from Figure A.2 let a second route cross over the first in such a way that the horizontal projections of each route cross at an angle θ. (Let θ be measured positive from the Y axis in the direction of the -X axis). Let this route have a climb angle of β_2 and protected airspace dimensions of V_2 and L_2. Let the centerline of the second route be an amount S above the centerline of the first route at the crossing point of their projections in the horizontal plane. The equations for the four planes for Route 2 are as follows:

$$X \cos \theta + Y \sin \theta = L_2$$

$$X \cos \theta + Y \sin \theta = -L_2$$

$$Z = \tan \beta_2 (-X \sin \theta + Y \cos \theta) + V_2 + S$$

$$Z = \tan \beta_2 (-X \sin \theta + Y \cos \theta) - V_2 + S$$

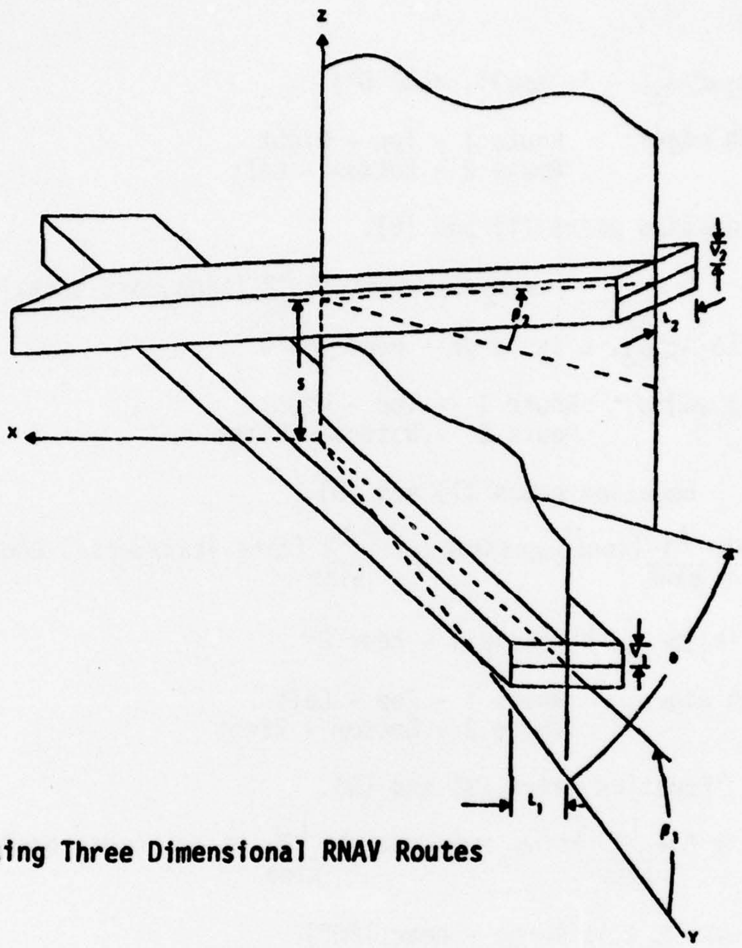


Figure A.2 Crossing Three Dimensional RNAV Routes

The two edges of interest for this route are the bottom right edge and the bottom left edge. The equations describing these edges are:

<u>Bottom - Right Edge</u>

$X \cos\theta + Y \sin\theta = L_2$

$Z = \tan\beta_2 (-X \sin\theta + Y \cos\theta) - V_2 + S$ Equation (5)

<u>Bottom - Left Edge</u>

$X \cos\theta + Y \sin\theta = -L_2$

$Z = \tan\beta_2 (-X \sin\theta + Y \cos\theta) - V_2 + S$ Equation (6)

For various combinations of β_1, β_2 and θ, different edge combinations will form the point at which the two routes will be the closest to touching. The technique that is used to solve for the separation between the route centerline S is to compute a value S_1 at which the edges of the two routes would touch. Then S is computed by adding an additional amount of separation B (called a buffer airspace) to S_1.

$S = S_1 + B$

<u>Case 1</u>: ($\beta_1 < \beta_2$, θ is small, near 0°)

Intersecting edges: Route 1 - Top - Right
Route 2 - Bottom - Left

Equation pairs (1) and (6).

$$S = V_1 + V_2 + B + \frac{L_1}{\sin\theta}(\tan\beta_2 - \cos\theta\tan\beta_1) + \frac{L_2}{\sin\theta}(\tan\beta_2\cos\theta - \tan\beta_1) \quad \text{Equation (7)}$$

<u>Case II</u>: ($\beta_1 < \beta_2$, θ is large - near 180°)

Intersecting edges: Route 1 - Top - Right
Route 2 - Bottom - Right

Equation pairs (1) and (5).

$$S = V_1 + V_2 + B + \frac{L_1}{\sin\theta}(\tan\beta_2 - \cos\theta\tan\beta_1) + \frac{L_2}{\sin\theta}(\tan\beta_1 - \tan\beta_2\cos\theta) \quad \text{Equation (8)}$$

<u>Case III</u>: ($\beta_1 > \beta_2$, θ is small - near 0°

Intersecting edges: Route 1 - Top - Left
Route 2 - Bottom - Right

Equation pairs (3) and (5).

$$S = V_1 + V_2 + B + \frac{L_1}{\sin\theta}(\tan\beta_1\cos\theta - \tan\beta_2) + \frac{L_2}{\sin\theta}(\tan\beta_1 - \tan\beta_2\cos\theta) \quad \text{Equation (9)}$$

<u>Case IV</u>: ($\beta_1 > \beta_2$ θ is large - near 180°)

Intersecting edges: Route 1 - Top - Right
Route 2 - Bottom - Right

Equation pairs (3) and (6).

S is the same as Equation (8).

Since Case I and II are the same except for the value of θ, it is of interest to identify the crossover point where both values of S are equal.

It can be seen that Equations (7) and (8) are equal when

$$\cos\theta = \frac{\tan\beta_1}{\tan\beta_2}$$

Similarly for Cases III and IV, the values of S are equal when

$$\cos\theta = \frac{\tan\beta_2}{\tan\beta_1}$$

In summary it can be noted that in all cases the quantities in brackets are zero or positive (for positive values of sin θ). Consequently, the separation S can be written simply as:

$$S = V_1 + V_2 + B + L_1 \left| \frac{\tan \beta_2 - \cos\theta \tan \beta_1}{\sin\theta} \right| + L_2 \left| \frac{\tan \beta_1 - \cos\theta \tan \beta_2}{\sin\theta} \right| \quad \text{Equation (10)}$$

(Note: For negative values of sin θ, four more edge combinations are possible. It can be easily shown that Equation (10) is valid for these four cases as well).

<u>Special Case</u>: $\beta_1 = \beta_2 = \beta$

Equation (9) becomes

$$S = V_1 + V_2 + B + \tan\beta(L_1 + L_2) \left| \frac{1 - \cos\theta}{\sin\theta} \right| \quad \text{Equation (11)}$$

As θ approaches zero the separation value S approaches

$$S = V_1 + V_2 + B$$

since it can be demonstrated by L' Hospital's Rule that

$$\frac{1 - \cos\theta}{\sin\theta}$$

goes to zero as θ goes to zero.

The parameters β_1, β_2 and θ are often the independent variables that the route designer can adjust to achieve a satisfactory design. The parameters V_1, V_2, L_1, L_2 and B are established from accuracy considerations of the airborne navigation system. The specific selection of values for these five parameters is considered in the following paragraphs.

A.3.2 Vertical Semitube Size

The statistical relationship between vertical semitube size, V_1 and V_2, and VNAV system accuracy is discussed in Appendix A of DO152. The vertical semitube size is shown to be the three sigma (3σ) value of a root-sum-square combination of vertical errors due to altimetry, VNAV equipment, vertical flight technical error and the along track navigation system errors projected into the vertical dimensions. Some typical error budgets for the first three error sources are shown in Table 1, Appendix A of DO152. They are repeated in the following table.

REPRESENTATIVE VERTICAL GUIDANCE ERROR

Budget in Feet (3 σ Values)

Error Source	Final Approach 5,000 Ft. MSL and below	Terminal Area 10,000 Ft. MSL and below	Enroute* 10,000 Ft. MSL and Above Level Flight	Enroute* 10,000 Ft. MSL and Above Ascent/Descent
Altimetry	± 90	± 200	± 250	± 250
VNAV	± 100	± 150	0**	± 220
Flight Technical	± 150	± 250	± 250	± 250
Total RSS (3σ)	± 200	± 350	± 350	± 420

The remaining term in the expression for the vertical semitube dimension is the projection of the along track navigation errors into the vertical dimension.

The along track navigation error term is based upon the use of a VORTAC type navigation system. The error term is composed of five error sources. They are:

Error Source	Standard Deviation Notation
Horizontal Computer	σ_{CH}
Ground VOR	$\sigma_{\theta, G}$
Airborne VOR	$\sigma_{\theta, A}$
Ground DME	$\sigma_{D,G}$
Airborne DME	$\sigma_{D,A}$

/Note/* Maximum operating altitude to be predicated on compliance with total accuracy tolerance.

/Note/** In the event that VNAV guidance is used in level flight while enroute, the incremental error component contributed by the VNAV equipment must be offset by a corresponding reduction in other error components, such as Flight Technical Error, to ensure that the total error budget is not exceeded.

Following the derivations of Appendix A of DO152, the standard deviation of the along track error (σ_{AT}) can be expressed as follows:

$$\sigma_{AT} = \sqrt{\sigma_{CH}^2 + (\sigma_{\theta,G}^2 + \sigma_{\theta,A}^2)\, D^2 \sin^2\psi + (\sigma_{D,G}^2 + \sigma_{D,A}^2) \cos^2\psi} \qquad \text{Equation (12)}$$

Where D = Horizontal distance to the VORTAC
ψ = Relative bearing to the VORTAC (bearing to VORTAC minus desired track)

The projection of the along track error into the vertical direction is accomplished by multiplying σ_{AT} by the tangent of the vertical path angle.

$$v = \sqrt{(3\sigma_V)^2 + (3\sigma_{AT} \tan \beta)^2} \qquad \text{Equation (13)}$$

Where $3\sigma_V$ is the vertical guidance error budget from Table 1 of Reference 5, σ_{AT} is computed from Equation (12) and β is the vertical path angle. The values which are used for the navigation system accuracy, σ_{AT} in Equation (13) are discussed in a later section.

A.3.3 Lateral Semitube Size

The establishment of lateral VNAV route dimensions is based upon the cross track error characteristics of VOR/DME navigation systems. This subject is discussed in Appendix D of RTCA DO140 and in Appendix D of Advisory Circular 90-45A. These documents discuss RNAV route widths which are based on 95% (2σ) probability contours of the cross track navigation errors. The cross track standard deviation, σ_{CT}, can be expressed as:

$$\sigma_{CT} = \sqrt{\sigma_{CH}^2 + (\sigma_{\theta,G}^2 + \sigma_{\theta,A}^2)\, D^2 \cos^2\psi + (\sigma_{D,G}^2 + \sigma_{D,A}^2) \sin^2\psi + \sigma_{PH}^2} \qquad \text{Equation (14)}$$

Where σ_{PH} = The standard deviation of the horizontal component of flight technical (pilotage) error.
The other standard deviations and symbols are described in the previous section.

As in the case with the along track error, the cross track error is a function of the relative bearing of the aircraft to the VORTAC. Often this geometrical dependence is simplified by selecting a constant route width which is based upon the maximum 2σ navigation error within some specified range of the VORTAC.

A.3.4 Parameter Selection

VNAV route dimensions used in this section were based upon the post-1982 time period in the FAA/Industry Task Force Report [1]. Slightly greater separation values would be necessary in the 1972-1977 and 1977-1982 time periods. The lateral route widths suggested in the Task Force Report are:

1.5 nm - Terminal Area (Up to 45 miles from the VORTAC)
2.5 nm - Enroute

These route widths are independent of the VORTAC geometry. Consequently, it is possible to use these route widths for the L_1 and L_2 values in Equation (10) In a similar manner it is possible to select a maximum value for along track error in the terminal and enroute airspace areas so that these values can be used to compute vertical route dimensions. In computing these values for along track error, the suggested navigation error budget for 1982 time period in the Task Force Report can be used. These values are:

$$\sigma_{\theta,G} = 0.5 \text{ degrees}$$

$$\sigma_{\theta,A} = 0.5 \text{ degrees}$$

$$\sigma_{D,G} = 0.05 \text{ nm}$$

$$\sigma_{D,A} = 0.125 \text{ nm}$$

$$\sigma_{CH} = 0.125 \text{ nm}$$

$$\sigma_{PH} = 0.50 \text{ nm}$$

Using Equation (14) to compute the maximum standard deviation for along track error (the maximum occurs at a relative bearing of 90° or 270°) the three sigma along track error figures are:

Terminal Area (Distance to tangent point = 45 nm) = 1.71 nm
Enroute (Distance to tangent point = 92 nm) = 3.43 nm

When projected into the vertical dimension these along track error parameters become:

Terminal Area - V_{AT} = 180 ft/degree of vertical path angle

Enroute - V_{AT} = 365 ft/degree of vertical path angle

The remaining parameters to be selected are the three sigma vertical errors for altimetry, VNAV computer and flight technical error. These values were given in Table 1 [5]. They are in summary:

Terminal Area V_0 = 350 ft.

Enroute (non level flight) V_0 = 420 ft.

The vertical semitube dimension is computed from a RSS combination of V_0 and V_{AT} multiplied by the specified vertical path angle (Equation (13)).

In certain congested airspace areas it may be desirable to have less separation than might otherwise be indicated by the tube dimensions described above. In these instances it may be possible to reduce the separation criteria by taking into account the geometrical considerations implied in Equations (12) and (14). By utilizing the relative bearing to the VORTAC at the point of intersection

of the crossing routes, reduced lateral and vertical semitube dimensions can be obtained. Three points were selected for analysis on this basis. They are located at a 90° (or 270°) relative bearing to the VORTAC. The relative bearing angle ψ can be expressed by the following equation:

$$\tan \psi = \frac{D_{tp}}{D_{at}}$$

where D_{tp} = distance from the VORTAC to the tangent point

D_{at} = distance along track from the aircraft to the tangent point

The geometric configuration is shown in Figure A.3

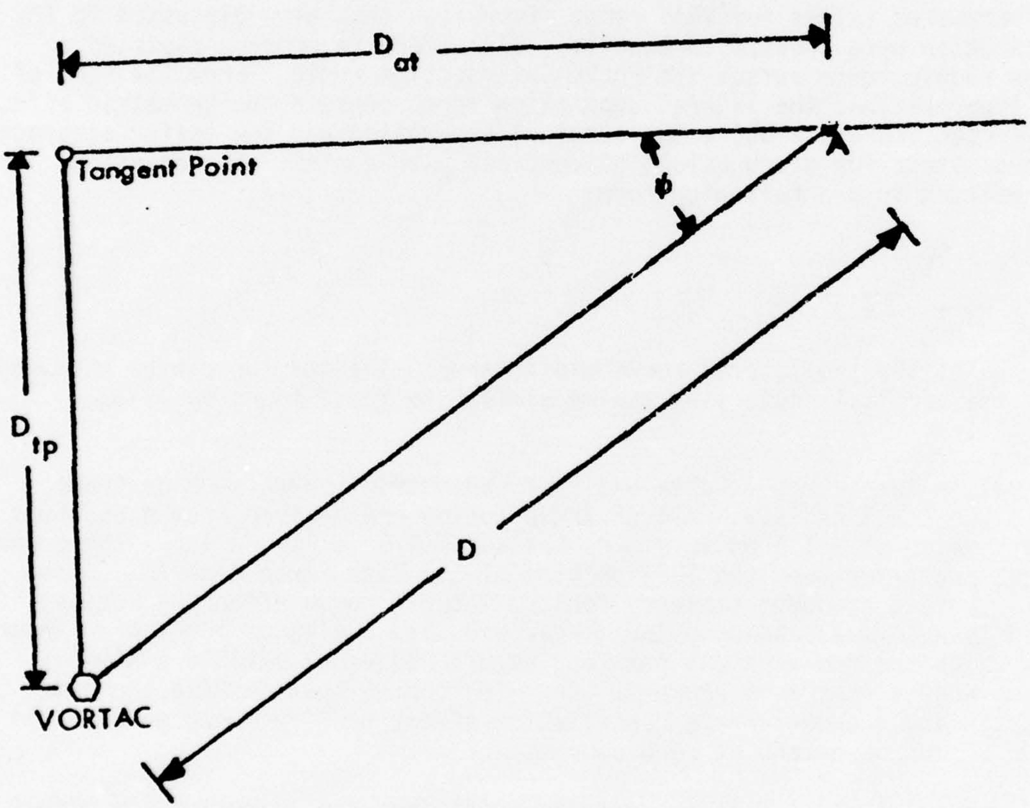


Figure A.3 Aircraft - VORTAC Geometry

The location of the three points and the corresponding route parameters as computed from Equations(12)and(14)are as follows:

D_{at}	D_{tp}	L	V_{AT}	V_0
0.	25.	1.07 nm	105 ft/degree	350 ft.
0.	45.	1.07 nm	180 ft/degree	350 ft.
0.	92.	1.07 nm	365 ft/degree	420 ft.

The last parameter which needs to be considered is the amount of airspace buffer zone between the two routes. This parameter, denoted as B in Equation (11), is set to 300 feet in DO152. That value is used in all of the analyses in this report.

A.3.5 Vertical Separation Analysis

The parameter values for VNAV route dimensions that were discussed in the previous section were applied to Equation(10)in order to produce plots of separation requirements versus the route intersection angle. From the form of (10) it is apparent that the lateral separation terms contain the geometric effect of the intersection angle while the vertical separation and the buffer airspace terms are constant for given values of vertical path angles. The equation could be written in the following form:

$$S = S_V + S_L$$

where $S_V = V_1 + V_2 + B$

and S_L contains the two lateral route width terms. The term S_V can be obtained by use of the vertical route size tables similar to those found in DO-152, Appendix C.

The values for S_L may be obtained from parametric curves such as those shown in Figures A.4 and A.5. All of these curves are derived from a constant route width value of $\pm$ 1.5 nm in Figure A.4 and $\pm$ 2.5 in Figure A.5. These route size values are taken from the 1982 portion of the Task Force Report. These curves all exhibit a common tendency for the lateral route effect on vertical separation to become exceedingly large near crossing angles of 160-180°. Those curves in which the two vertical path angles are not equal exhibit a similar tendency at angles near zero degrees. Crossing routes that do have the same vertical path angle experience a cancellation effect near zero degrees and the curves for S_L approach zero at zero degrees.

In Figures A.4 and A.5 it is quite apparent that the lateral route effect on vertical separation can best be minimized by keeping route crossing angles between 35° and 100° for situations in which at least one of the vertical path angles is less than or equal to 3°.

Figures A.6 and A.7 show the total vertical separation value S as a function of route intersection angle for lateral route widths of $\pm$ 1.5 nm and $\pm$ 2.5 nm respectively. These curves have the same general shape of the curves for S_L but they are all biased upward by the appropriate value for S_V.

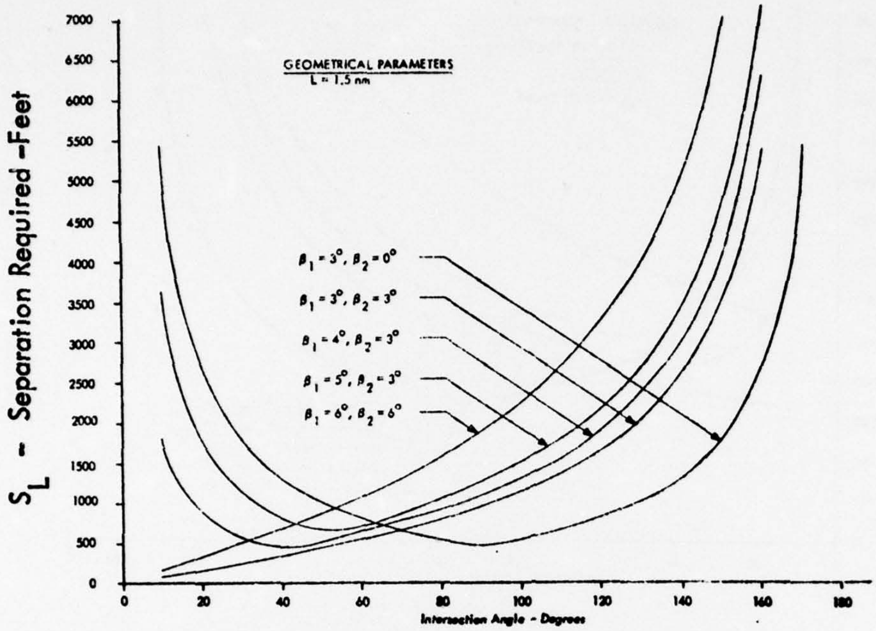


Figure A.4 Vertical Separation Caused by Lateral Route Width of ± 1.5 nm.

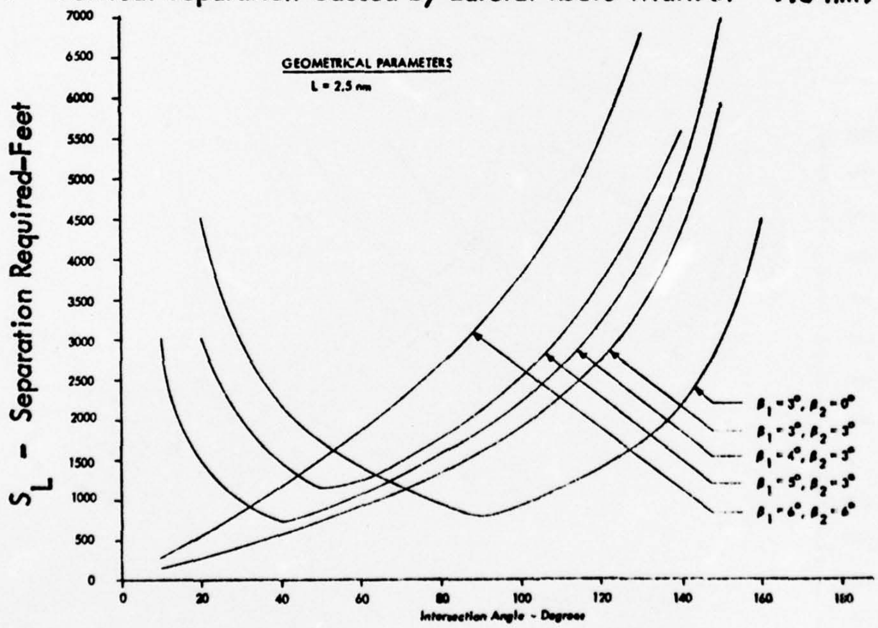


Figure A.5 Vertical Separation Caused by Lateral Route Width of ± 2.5 nm.

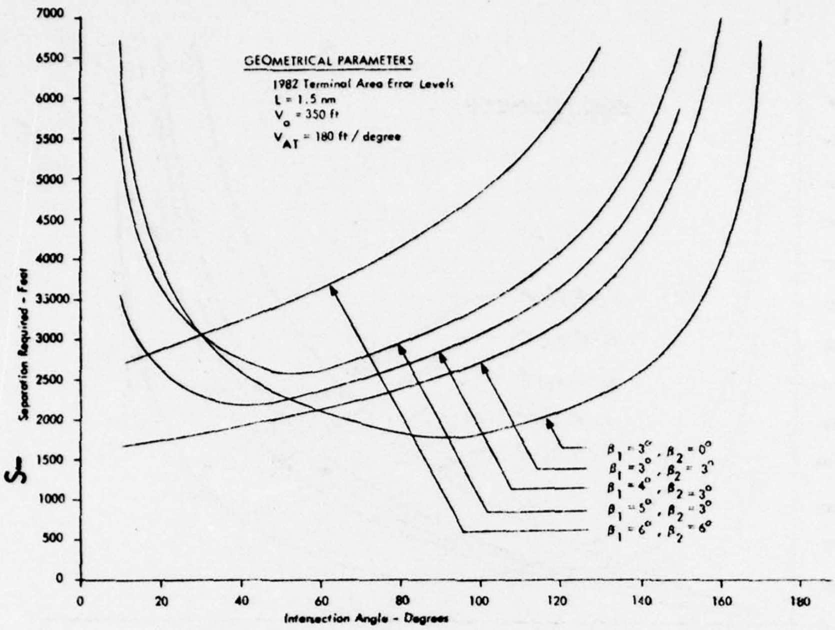


Figure A.6 Vertical Separation Requirements -- Terminal Area

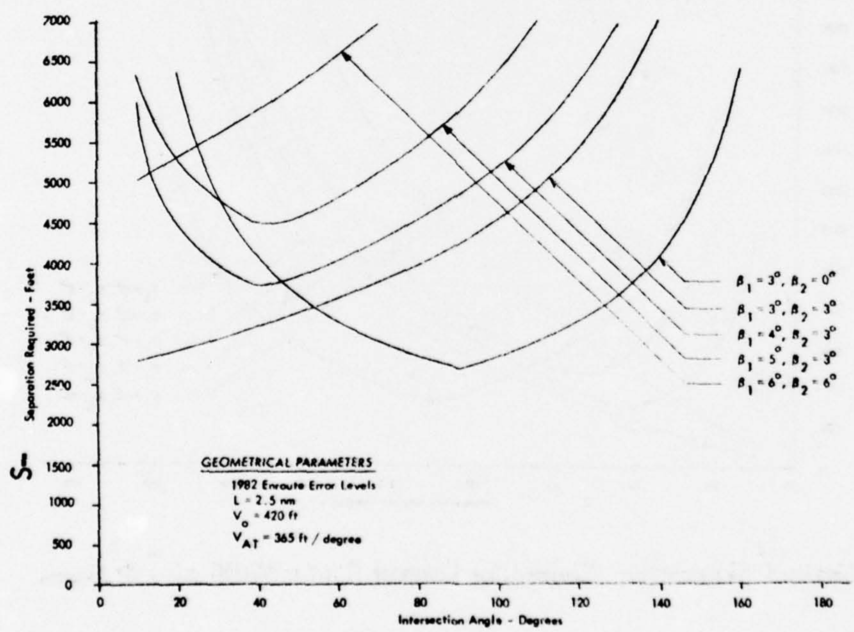


Figure A.7 Vertical Separation Requirements - Enroute

In extremely congested airspace areas it may be possible to use a reduced vertical route separation criteria. This can be accomplished by taking advantage of the dependence of the route size equations for L and V on the relative bearing to the VORTAC. This technique of taking advantage of specific geometry situations for reduced route sizes was also used in Advisory Circular 90-45A for the lateral route width determination. To demonstrate this route separation reduction phenomena, reduced values of S were computed for two points in the terminal area at tangent point distances of 25 and 45 nm, and one point in the enroute airspace at a tangent point distance of 92 nm. An along track distance of 0 nm was used for all three cases (relative bearing is 90° and 270° in all instances). The terminal area curves are shown in Figures A.8 and A.9 and the enroute curves are shown in Figure A.10. These curves exhibit reduced separation values of 138 and 303 feet for a 3° route-level route crossing at 90° in the terminal area and 456 feet in the enroute case.

In order to minimize the vertical separation requirements, route crossings in the range of 35° and 110° are required for routes having gradients of up to six degrees.

A.4 THREE-DIMENSIONAL TURN POINTS AND PARALLEL OFFSETS

The navigation, operational, and separation problems associated with the use of parallel offsets in climbing or descending situations are many and complex. In the following discussion, fixed gradient 3D routes are used to illustrate some of the problems associated with crossing route turn points and climbing/descending parallel offsets.

3D parallel offsets may be defined with a vertical path angle (VPA) equal to that of the parent route for straight 3D segments. When a 3D segment contains a turnpoint, offset routes with the same VPA as the parent route will experience an altitude discontinuity at the turn point. If this altitude discontinuity is to be avoided, the offset routes must be defined such that they emanate from a point on the bisector of turn angle, with the result that their VPAs differ from the parent route VPA.

Two basic types of VNAV systems are in existence at the present time. One system, which shall be denoted as the "simple" sytem, makes use of flat earth approximations and VORTAC station-referenced geometry in order to perform the 2D and 3D position computations. The more sophisticated VNAV systems make use of digital computer technology to solve the 3D aircraft position equations through the use of spherical or spheroidal geometry. These systems are referred to in this report as "ARINC" systems because they are described by specifications that are developed by the Airline Electronic Engineering Committee of Aeronautical Radio, Inc. (ARINC).

There are two basic techniques for flying a constant 3D offset around a turn. The first technique is illustrated in Figure A.11 using a simple RNAV system.

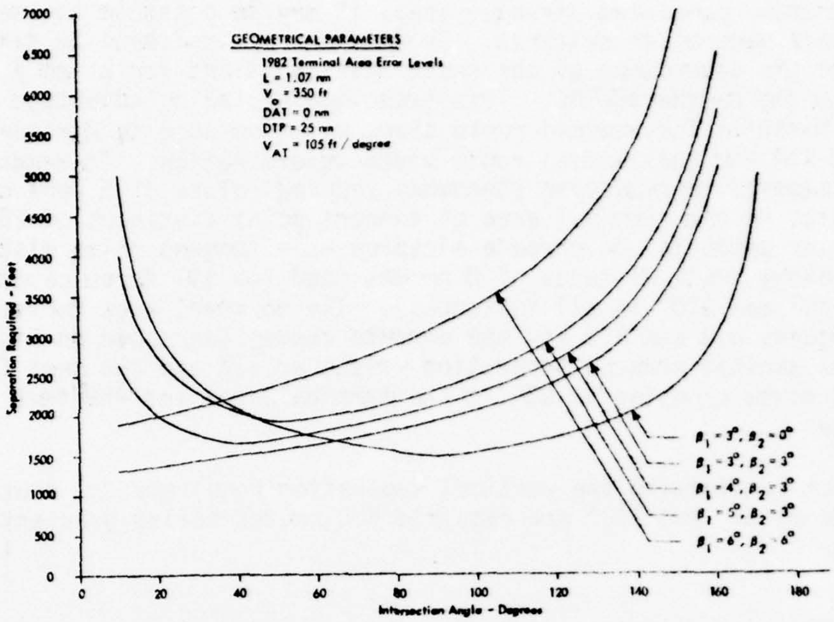


Figure A.8 Reduced Terminal Area Vertical Separation Requirements, D = 25nm.

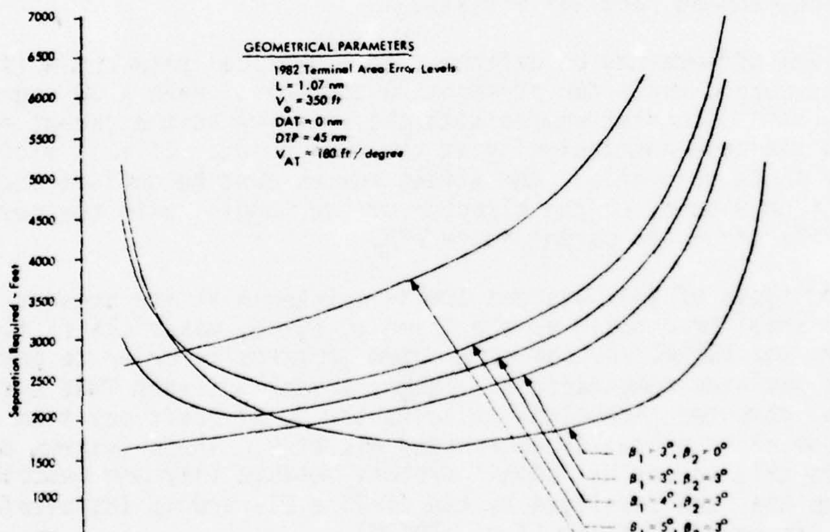


Figure A.9 Reduced Terminal Area Vertical Separation Requirements, D = 45nm.

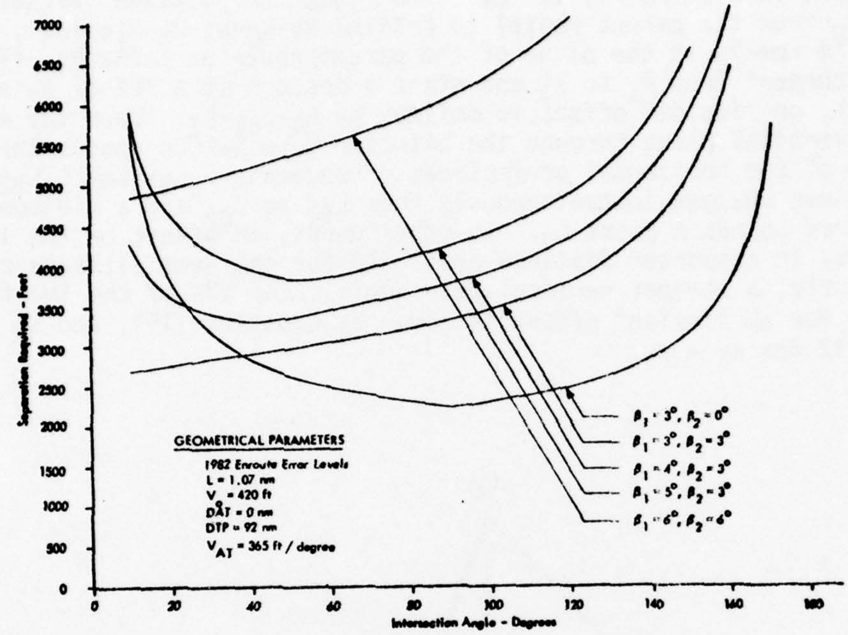


Figure A.10 Reduced Enroute Vertical Separation Requirements, D = 92 nm.

The parent route in Figure A.11 is defined by segment P_0P_1 at a VPA of β_1 and by segment P_1P_2 at a VPA of β_2. The lateral track angle from segment P_0P_1 to P_1P_2 (at the turn point P_1) is $\Delta\psi$. The right, or "outside" offset (at a distance R_0P_0 from the parent route) is defined by R_0-R_1-R_B-R_1'; i.e., the aircraft would remain in the plane of the parent route to point R_1, fly level "around the corner" from R_1 to R_1' and start a descent at a VPA of β_2 at point R_1'. The left, or "inside" offset is defined by L_0-L_{B1}-L_2. When the aircraft reaches the vertical plane through the bisector R_BL_B (which passes through the intersection of the horizontal projections of segments L_0L_{B1} and L_1L_{B2}) the desired altitude changes instantaneously from L_{B1} to L_{B2} and a *minimum* VPA of β_{L2} is required to reach point L_2. In other words, an offset on the inside of a turn results in a shorter distance available for the same altitude change, and consequently, a steeper vertical path angle. The VPA of the leg following a turn point for an "inside" offset is given by Equation (15), and is plotted in Figure A.12 for $\beta_1 = \beta_2$.

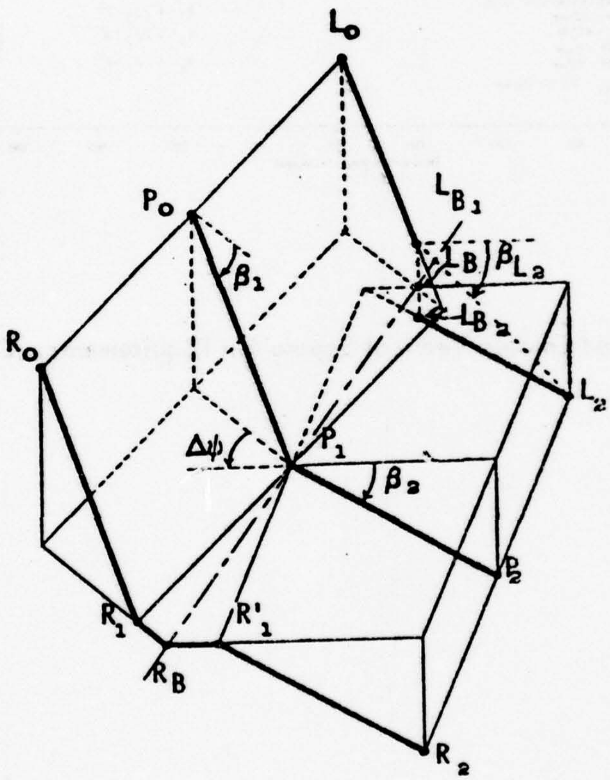
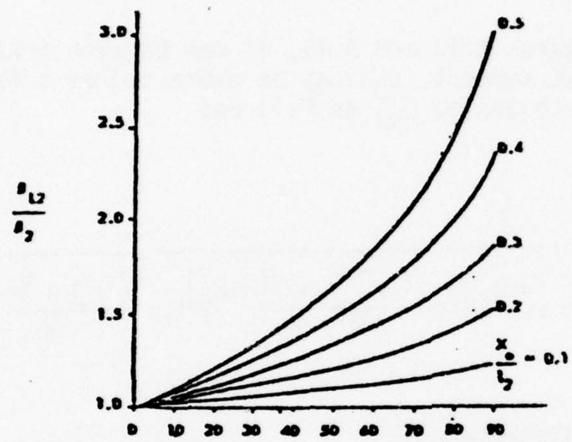


Figure A.11 Offset Geometry "Simple" System

$$\beta_{L2} = \frac{\beta_2 + \beta_1 \frac{X_0}{l_2} \tan \frac{\Delta\psi}{2}}{1 - \frac{X_o}{l_2} \tan \frac{\Delta\psi}{2}}$$

Equation (15)



$\Delta\alpha$ (degrees)
VPA for 2nd Leg Inside
Offset When $\beta_1 = \beta_2$

Figure A.12 Inside Offset VPA

The significance of Figure A.12 may be illustrated by an example: Consider an aircraft flying on a 6 mile left offset at a vertical path angle, β_1, of -3 degrees. The next leg of the parent route is 20 miles in length, has a VPA, β_2, of -3 degrees and has a track 90 degrees to the left of the present leg. Upon intercepting the 6 mile left offset of the next leg, the aircraft must attain an average VPA of at least 1.85 x 3 degrees, or 5.55 degrees.

The crossing route separation required for the offset route configuration illustrated in Figure A.11 may be computed directly from Equation (10) with respect to either segment 1 or segment 2, and with a route width equal to parent route width plus offset distance. To continue the example given above, consider a route crossing in the vertical plane defined by R_1 - L_1 in Figure A.11 with VPA of -3 degrees. In the terminal area, the vertical separation required between the parent route and the crossing route is determined from Figure A.6 as 2500 feet. The crossing route over both the parent route and the inside offset similarly requires a separation of 2500 feet over the offset, which results in a 4400 foot separation over the parent route. The crossing

route under the parent route and the inside offset route is coincident with the parent route segment 2, since the course change is 90 degrees. The vertical separation is, therefore, independent of route width and reduces to 1540 feet.

The second, or "ARINC" system technique is illustrated in Figure A.13. In this case, since the offset route turn point is located on the bisector of the angle between adjacent route segments, the length of the second offset segment is dependent upon the track angle of the third segment, as illustrated in Figure A.14.

From an examination of Figures A.13 and A.14, it can be seen that the vertical path angle of an offset segment, β_0, may be expressed as a function of the parent route vertical path angle, β_p, as follows:

$$\beta_0 = \beta_p \frac{1}{1 + \frac{X_0}{l_p}\left[k_0\left|\tan\frac{\psi_{n-1} - \psi_n}{2}\right| + k_1\left|\tan\frac{\psi_n - \psi_{n+1}}{2}\right| + k_2\left|\tan\frac{\psi_{n+1} - \psi_{n+2}}{2}\right|\right]} \qquad \text{Equation (16)}$$

Where: X_0 = offset distance

l_p = length of parent route segment "n' in the horizontal plane

ψ_n = track angle of route segment n

k_1 = -1, 0, or +1

K_2 = -1, 0, or +1

Figures A.14a through A.14d depict possible route configurations for a constant parallel offset on one side of a parent route. The vertical path angle required on a given segment of an offset 3D route, as given by Equation (16) is of interest because of aircraft performance limitations. The vertical separation requirements for routes crossing above and below the parent-offset route configurations depicted in Figure A.14 are also of interest from both airspace utilization and procedural viewpoints. Vertical separation required for a crossing route with respect to the parent route and the offset route are given by Equations (17) and (18) respectively (Ref. Section A.3).

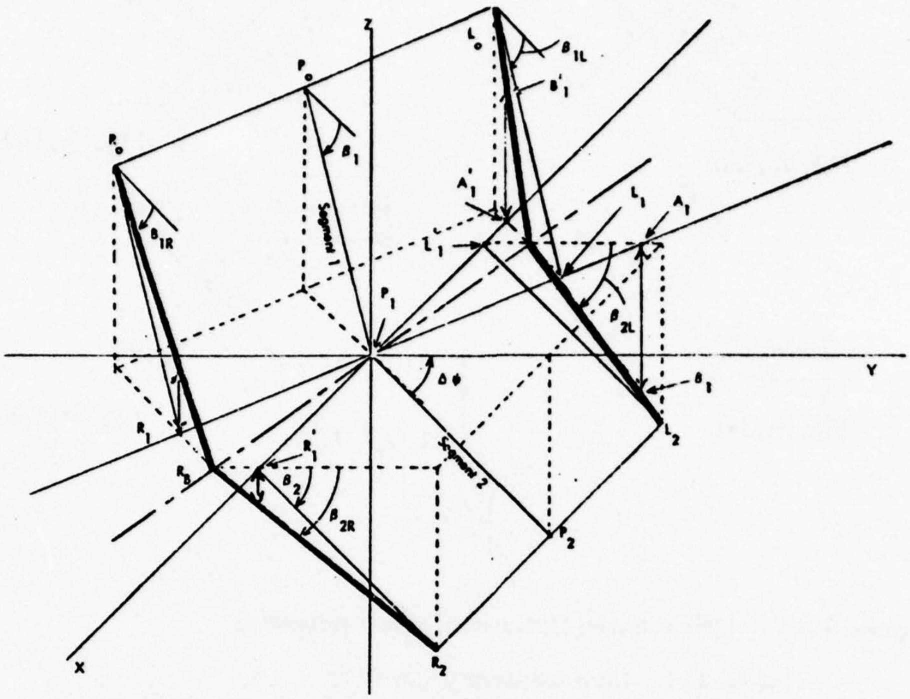


Figure A.13 "ARINC" System Offset Route Geometry

$$S_{pc} = V_p + V_c + B + L_p \left| \frac{\tan \beta_c - \cos \theta_i \tan \beta_p}{\sin \theta_i} \right| + L_c \left| \frac{\tan \beta_p - \cos \theta_i \tan \beta_c}{\sin \theta_i} \right| \quad \text{Equation (17)}$$

where S_{pc} = vertical separation between parent route and crossing route

p = parent route segment

c = crossing route

V = vertical semitube dimension

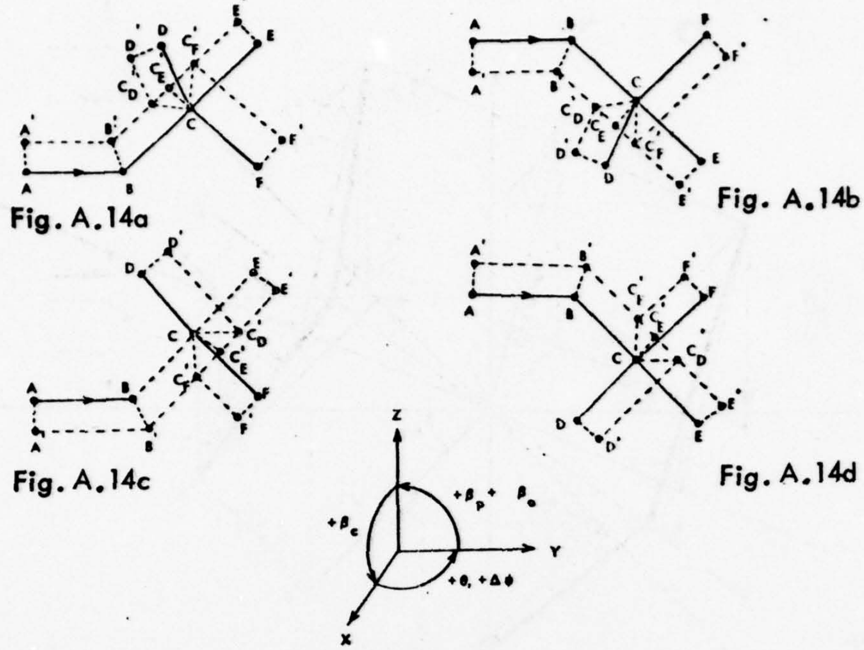


Figure A.14 Offset Route Horizontal plane geometry

Table A.1 Turn Geometry Coefficients

FIG.	Route Con.	Turn Pnt.	Leg n	ko_n	$k1_n$	$k2_n$	$k3_n$	$k4_n$	Leg n+1	ko_{n+1}	$k1_{n+1}$	$k2_{n+1}$	$k3_{n+1}$	$k4_{n+1}$
A.14a	ABCD	B	AB	0	-1	0	+1	-1	BC	0	-1	-1	+1	+1
	ABCD	C	BC	-1	-1	0	+1	-1	CD	0	-1	0	+1	+1
	ABCE	B	AB	0	-1	0	+1	-1	BC	0	-1	0	+1	+1
	ABCE	C	BC	-1	0	0	0	-1	CE	0	0	0	0	+1
	ABCF	B	AB	0	-1	0	+1	-1	BC	0	-1	+1	+1	+1
	ABCF	C	BC	-1	+1	0	+1	-1	CF	0	+1	0	+1	+1
A.14b	ABCD	B	AB	0	-1	0	-1	+1	BC	0	-1	-1	-1	-1
	ABCD	C	BC	-1	-1	0	-1	+1	CD	0	-1	0	-1	-1
	ABCE	B	AB	0	-1	0	-1	+1	BC	0	-1	0	-1	-1
	ABCE	C	BC	-1	0	0	0	+1	CE	0	0	0	0	-1
	ABCF	B	AB	0	-1	0	-1	+1	BC	0	-1	+1	-1	-1
	ABCF	C	BC	-1	+1	0	-1	+1	CF	0	+1	0	-1	-1
A.14c	ABCD	B	AB	0	+1	0	-1	+1	BC	0	+1	+1	-1	-1
	ABCD	C	AB	+1	+1	0	-1	+1	CD	0	+1	0	-1	-1
	ABCE	B	AB	0	+1	0	-1	+1	BC	0	+1	0	-1	-1
	ABCE	C	BC	+1	0	0	0	+1	CE	0	0	0	0	-1
	ABCF	B	AB	0	+1	0	-1	+1	BC	0	+1	-1	-1	-1
	ABCF	C	BC	+1	-1	0	-1	+1	CF	0	-1	0	-1	-1
A.14d	ABCD	B	AB	0	+1	0	+1	-1	BC	0	+1	+1	+1	+1
	ABCD	C	BC	+1	+1	0	+1	-1	CD	0	+1	0	+1	+1
	ABCE	B	AB	0	+1	0	+1	-1	BC	0	+1	0	+1	+1
	ABCE	C	BC	+1	0	0	0	-1	CE	0	0	0	0	+1
	ABCF	B	AB	0	+1	0	+1	-1	BC	0	+1	-1	+1	+1
	ABCF	C	BC	+1	-1	0	+1	-1	CF	0	-1	0	+1	+1

For crossing route above the parent route/offset route:

$$\theta_i = \theta_n$$
$$\beta_a = \beta_n$$
$$\beta_p = \beta_n$$
$$l_p = l_n$$

For crossing route below the parent route/offset route:

$$\theta_i = \theta_{n+1}$$
$$\beta_a = \beta_{n+1}$$
$$\beta_p = \beta_{n+1}$$
$$l_p = l_{n+1}$$

$$S_{oc} = V_o + V_c + B + L_o \left| \frac{\tan\beta_c - \cos\theta_i \tan\beta_o}{\sin\theta_i} \right| + L_c \left| \frac{\tan\beta_o - \cos\theta_i \tan\beta_c}{\sin\theta_i} \right| \qquad \text{Equation (18)}$$

Where S_{oc} = vertical separation between offset route and crossing route

o = offset route segment

c = crossing route

The vertical separation above the parent route <u>at the turnpoint</u> for a route crossing both the parent route and the offset is the larger of S_{pc} and $(S_{oc} + H_o)$, where H_o is the additional separation above or below the parent route turn point due to the altitude of the point at which the offset segment (or its extension) intersects the crossing route vertical plane:

$$H_o = X_o \tan\beta_o \left[k_3 \tan\frac{\Delta\psi}{2} + k_4 \tan\left(\theta_i - \frac{\pi}{2}\right) \right] \qquad \text{Equation (19)}$$

where, $\Delta\psi = \psi_n - \psi_{n+1}$ (i.e. positive in counter clockwise direction)

θ_i = crossing angle in horizontal plane with respect to parent route segment i:

i = n for crossing route above parent route
i = n + 1 for crossing route below parent route

The subscripts and constants applicable to Equations(16-19)for each route configuration depicted in Figure A.14 are given in Table A.1.

The crossing route vertical separation required for the "sophisticated" system technique may be greater or less than that for the "simple" system technique, depending upon the geometry of the crossing route situation. Figure A.15 gives the crossing route vertical separation for a straight segment route, B, crossing at the turnpoint of another route, A, with a 6 nm "outside" offset. All conditions are shown in Figure A.16, $\beta_A = 3°$; $\beta_B = 0°$, and the length of leg 2 of route A is 25 nm. The geometry is as depicted in Figure A.14c, configuration ABCE.

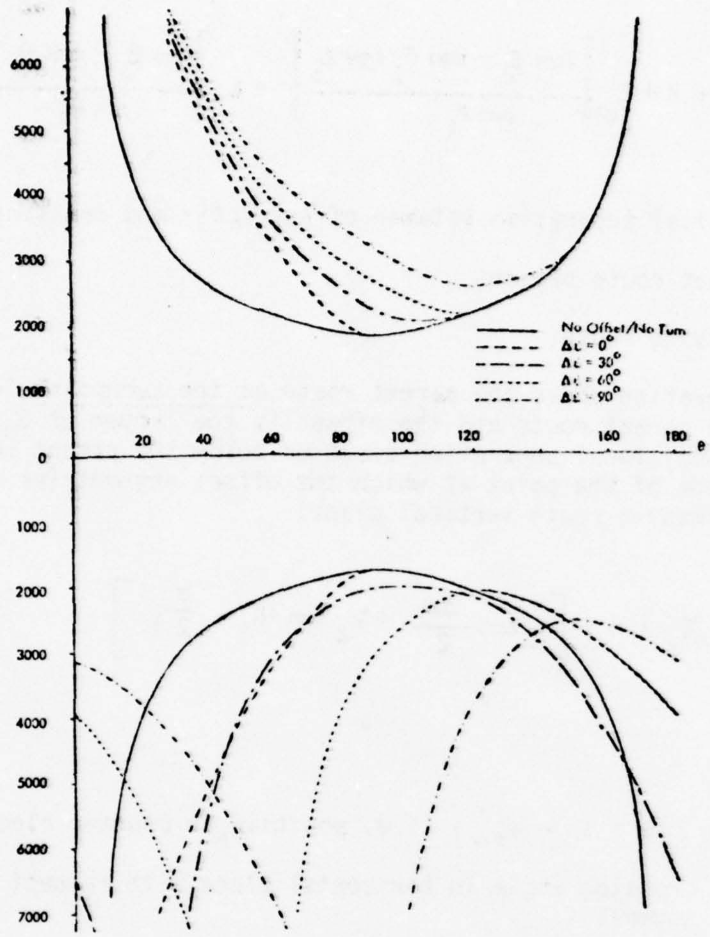


Figure A.15 Vertical Separation for Turn Routes - "Sophisticated" System
(6nm offset, 25nm legs)

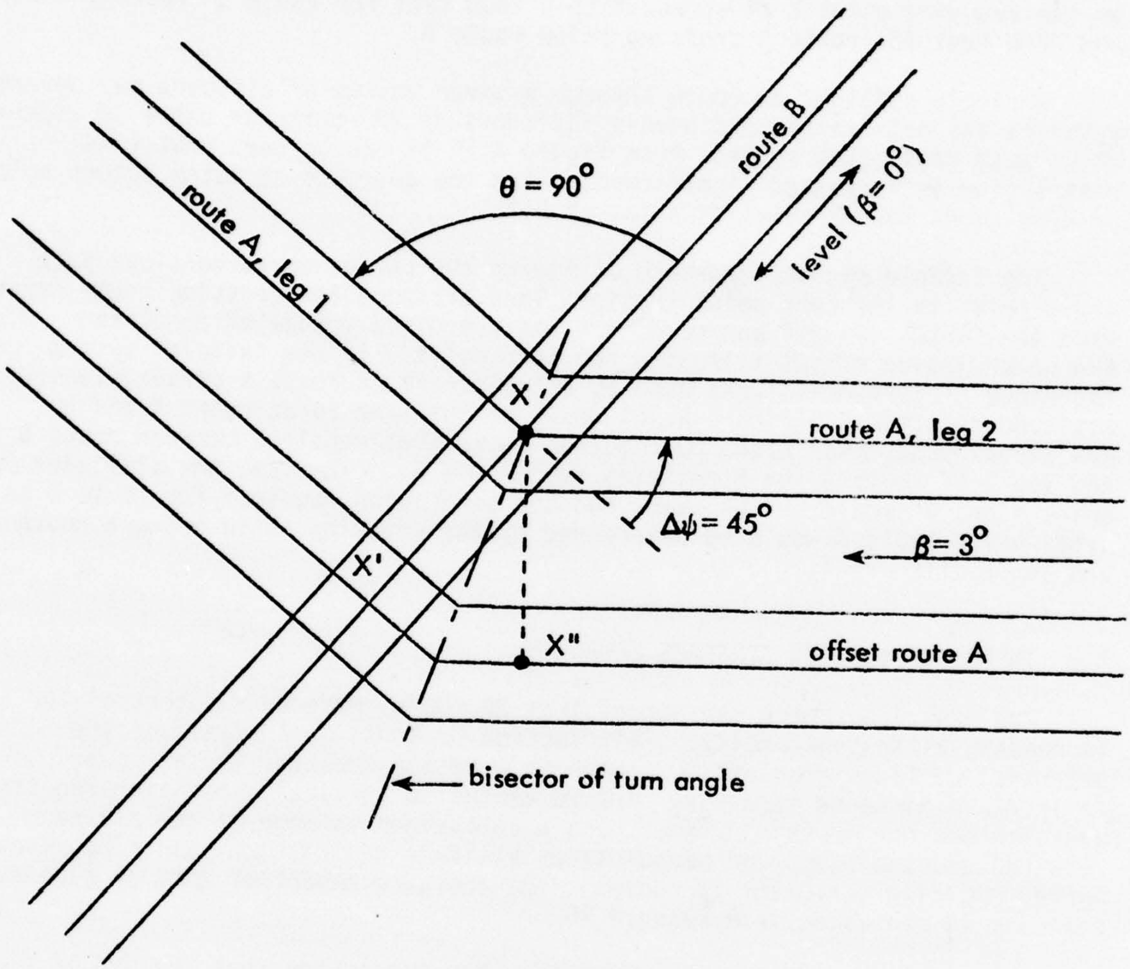


Figure A.16
Projection of Crossing Routes in Horizontal Plane

An example is illustrated on Figure A.15. The specific geometry depicted in Figure A.16 would require vertical separation between the route centerlines at the crossing point X of approximately 2400 feet for route B crossing above, and 2600 feet for route B crossing below route A.

A single straight 3D route through a given volume of airspace may severely restrict the orientation and usable altitudes of 2D routes or other 3D routes which must cross that route. From Figure A.15 it can be seen that this restriction is increased significantly when the 3D route contains a turn point, or provisions for parallel offsets, or both.

The "simple system" approach of flying the parent route vertical path angle prior to the turn point requires less airspace for crossing route separation than the "ARINC system" approach, but has the disadvantage of requiring a steeper VPA on an inside offset following the turn point. If the "simple" system technique (Figure A.11) were used by all aircraft on route A offset, their altitude at point X' (Figure A.16) would be the same as at point X and no additional separation would be required above that required between route B and leg 1 of route A for B crossing over route A. Likewise, the altitudes at point X and X' would be the same, and the separation required for route B to cross below route A would be determined by the crossing angle between route B and leg 2 of route A.

A.5 IMPACT OF VNAV ON AIRSPACE CAPACITY

The RNAV Task Force considered that 3D routes offered a potential for increasing airspace capacity. This section presents an analysis of the potential of fixed gradient 3D routes as a design tool for the airspace planner to increase airspace capacity. The 2D versus 3D vertical separation requirements are examined for crossing routes, and a comparison is made of the airspace required and the number of waypoints or altitude restriction points required for 2D and fixed gradient 3D routes. The economic impact of VNAV on airspace capacity is contained in Reference 16.

The results of this analysis support the conclusion that the use of fixed gradient 3D routes for procedural separation and/or the requiring of 3D capability for entry into certain airspace does not appear to offer sufficient payoff in either airspace capacity or operational utility to warrant consideration. A corollary of this conclusion is that the terminal area design approach recommended in Section 8 need not be constrained by a requirement for fixed gradient 3D routes. Therefore, optimum arrival and departure routes may be designed on the basis of providing the shortest path length and most efficient altitude profiles for 3D equipped aircraft, and 2D equipped aircraft can also utilize these profiles. Additional economic benefits are available to 3D equipped aircraft through pilot selection of 3D gradients.

A.5.1 Separation Requirements

Vertical and horizontal separation have always been provided independently, i.e. the joint probability distribution is not considered in assigning separation, and both the horizontal and vertical separation requirements are met in assigning altitude restrictions. The technique selected for VNAV

separation is the time-proven separation concept of utilizing 2 σ errors in the horizontal plane and 3 σ errors in the vertical plane. The along track error, reflected into the vertical plane, is not directly additive, but is considered a part of an error budget whose elements are combined in an RSS manner.

When the along track error is considered in this way, crossing routes may be described as "tubes" with rectangular cross sections whose dimensions describe the 2 σ horizontal, and 3 σ vertical, total system errors and the required vertical separation between the center lines of these routes may be derived geometrically by placing the routes such that edges of the "boxes" just touch. This technique was applied in the derivation of vertical separation requirements in Section A.3.

The consideration of along track error as a part of the vertical error budget is certainly an acceptable technique. It does not, however, provide for a convenient method of computing the horizontal location of positions at which altitude restrictions may be applied to insure vertical separation of crossing RNAV (2D) routes, or for the crossing of a 2D route by a 3D route where an altitude restriction is necessary on the 2D route.

A.5.2 RNAV Separation (2D/2D)

Consider the crossing route situation depicted in Figure A.17. The route widths L_1 and L_2 represent the total 2 σ cross track error of each route. The routes are both descending, as indicated by the arrows on the route centerline, and it is assumed that route #1 will cross over route #2. It is desired to establish two altitude restriction points to provide for procedural separation.

In determining the point along route #1 at which to place the restriction, the effective width of route #2 must be considered. It consists of two elements: 1) the width of route #2 at the crossing angle θ: $\left|\frac{L_2}{\sin\theta}\right|$, and 2) the additional width of route #2 due to the width of route #1: $\left|\frac{L_1}{\tan\theta}\right|$.

The longitudinal uncertainty of position on route #1 must also be taken into account. (This is the error which was accommodated in the VNAV case by making it a part of the vertical error budget). This along track error on route #1 may be considered as an additional element in the effective route width of route #2, but it should not be combined RSS, as it was in the VNAV case. In the VNAV case, the along track error on route #1 is but one element of the VNAV error on route #1. In this case (RNAV), it is the total error, along one coordinate of the horizontal plane for route #1, and is being combined with the other elements of the effective width of route #2 only for geometric convenience. The RTCA committee on Area Navigation, SC-116E, recommended the inclusion of along track error, reflected into the vertical, as part of the RNAV error budget and it is included in this comparison of 2D and 3D operation to maintain consistency. The selection of an along track error equal to cross track error is perhaps overly conservative and implies an error distribution which is not wholly representative of any existing RNAV system. However, consideration of any specific postulated error distribution may be accomplished

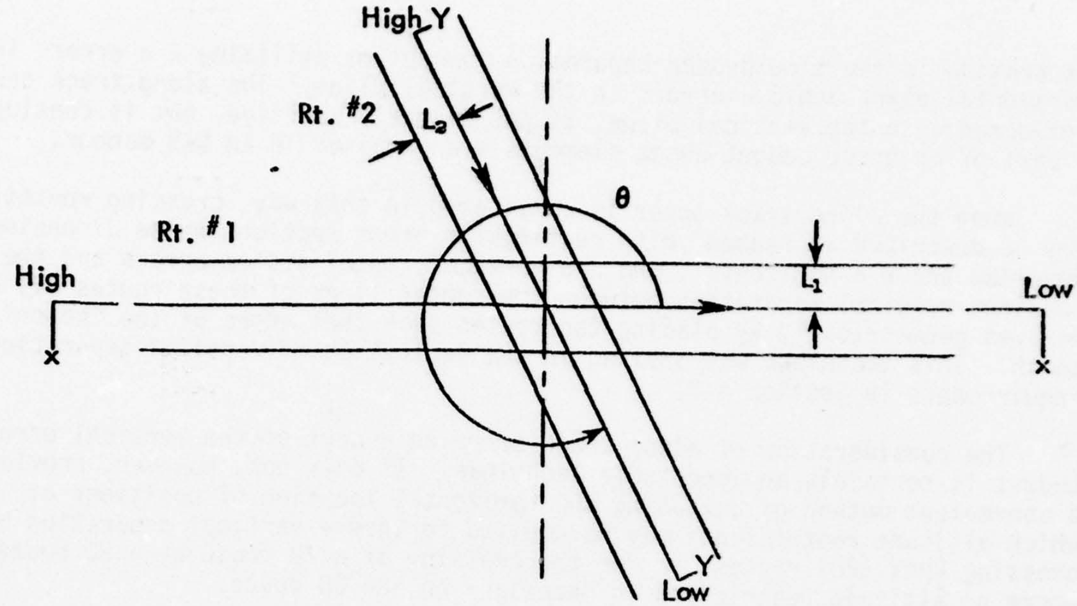


Figure A.17a Plan View

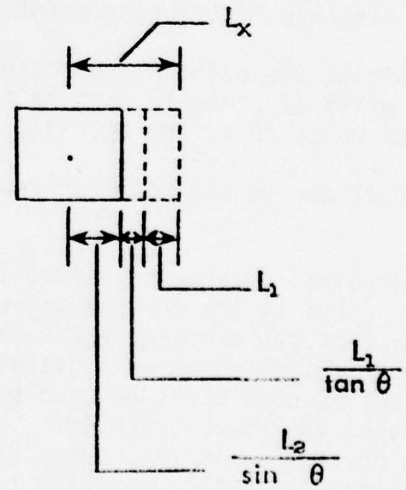


Figure A.17b Vertical Cross-Section of Route #2 at Intersection

Figure A.17 Crossing RNAV Routes

by modifying the along track error terms in the equations which are developed below. Both the inclusion of the maximum along track error in the 2D case, and the RSS combination of the maximum along track error in the 3D case, combine to favor 3D in comparison with 2D separation in the following analysis.

Referring again to Figure A.17, L_x is defined as the effective width of route #2 at the intersection of route #1, then for purposes of route separation L_x is as shown in Table A.2 for various values of the crossing angle θ.

Table A.2 Effective Width of Crossing Route for Purpose of Altitude Separation

θ = Crossing Angle	L_x = Effective Route Width
$0 < \theta \leq \frac{\pi}{2}$	$\frac{L_1}{\tan\theta} + \frac{L_2}{\sin\theta} + L_1$
$\frac{\pi}{2} < \theta \leq \pi$	$-\frac{L_1}{\tan\theta} + \frac{L_2}{\sin\theta} + L_1$
$\pi < \theta \leq \frac{3\pi}{2}$	$\frac{L_1}{\tan\theta} - \frac{L_2}{\sin\theta} + L_1$
$\frac{3\pi}{2} < \theta \leq 2\pi$	$-\frac{L_1}{\tan\theta} - \frac{L_2}{\sin\theta} + L_1$

Since L_x is zero or positive for all values of θ, L_x may be expressed as:

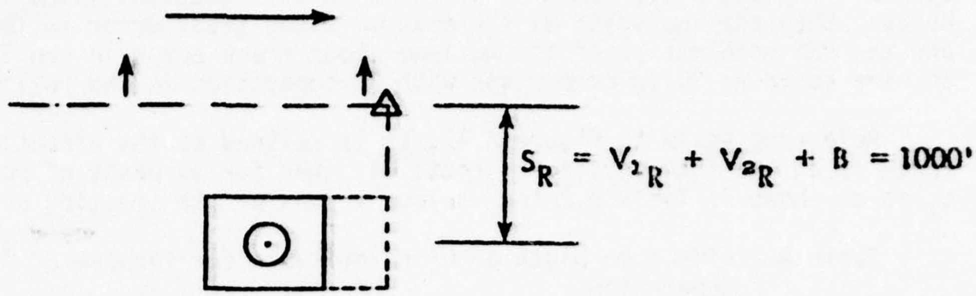
$$L_x = \left|\frac{L_2}{\sin\theta}\right| + \left|\frac{L_1}{\tan\theta}\right| + L_1 \qquad \text{(Equation (20)}$$

and similarly, by inspection:

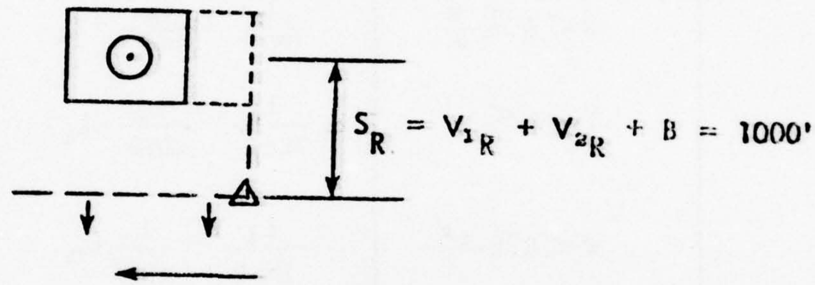
$$L_y = \left|\frac{L_1}{\sin\theta}\right| + \left|\frac{L_2}{\tan\theta}\right| + L_2 \qquad \text{(Equation (21)}$$

The location of altitude restriction points for crossing route separation with an example of altitude restrictions is given in Figure A.18.

For 2D Separation: (x - x view)



For 2D Separation: (y - y view)



For 2D Separation: (Plan View)

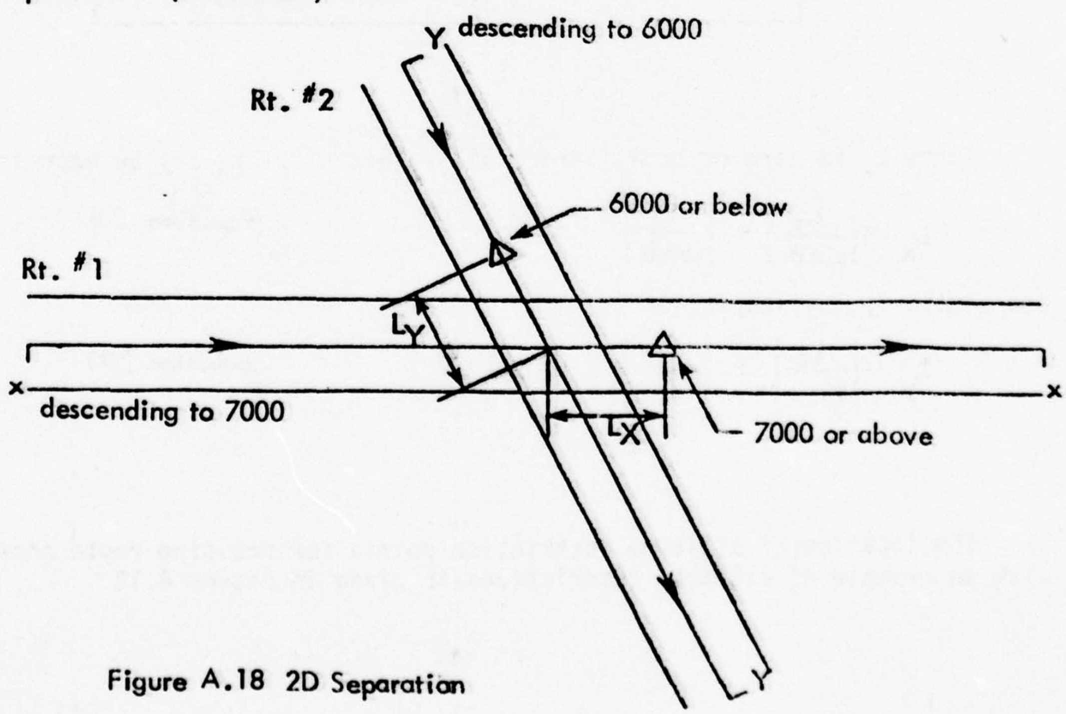


Figure A.18 2D Separation

A special case of the 2D crossing route situation is depicted in Figure A.19 where route #1 merges into a route parallel with route #2 at an offset distance of $2L_2$.

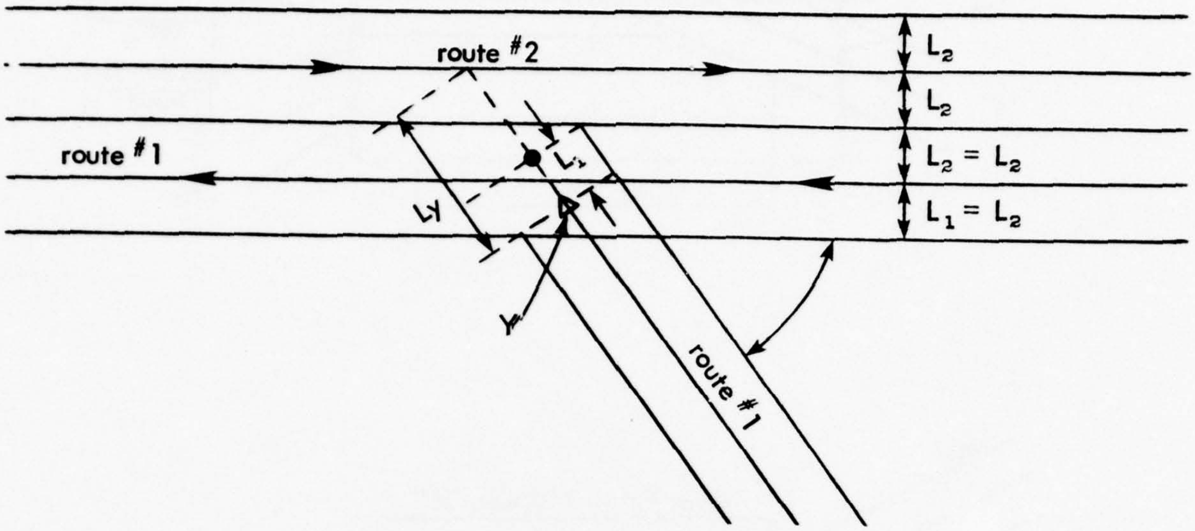


Figure A.19 Merging Parallel Routes

If route #1 were to continue across route #2 at the angle θ, altitude separation would have to be provided starting at waypoint Y. In the merging case, however, route #1 can be at the same altitude as route #2 since the contribution of along track error on route #1 to parallel offset distance requirements approaches zero as an aircraft makes the turn onto the parallel route, and with some type of turn anticipation the aircraft on route #1 will not violate route #2 airspace.

A.5.3 2D/3D Separation

Now consider a 3D route (#2) crossing a 2D route (#1) with θ defined such that the high end of route #2 would overlay the high end of route #1 (and the + axis of a right hand coordinate system) when $\theta = 0$, as illustrated in Figure A.20.

The vertical separation between the center lines of intersecting 3D routes was derived in Section A.3 and may be expressed as:

$$S = V_1 + V_2 + B + L_1 \left| \frac{\tan\beta_2 - \cos\theta \tan\beta_1}{\sin\theta} \right| + L_2 \left| \frac{\tan\beta_1 - \cos\theta \tan\beta_2}{\sin\theta} \right| \qquad \text{Equation (22)}$$

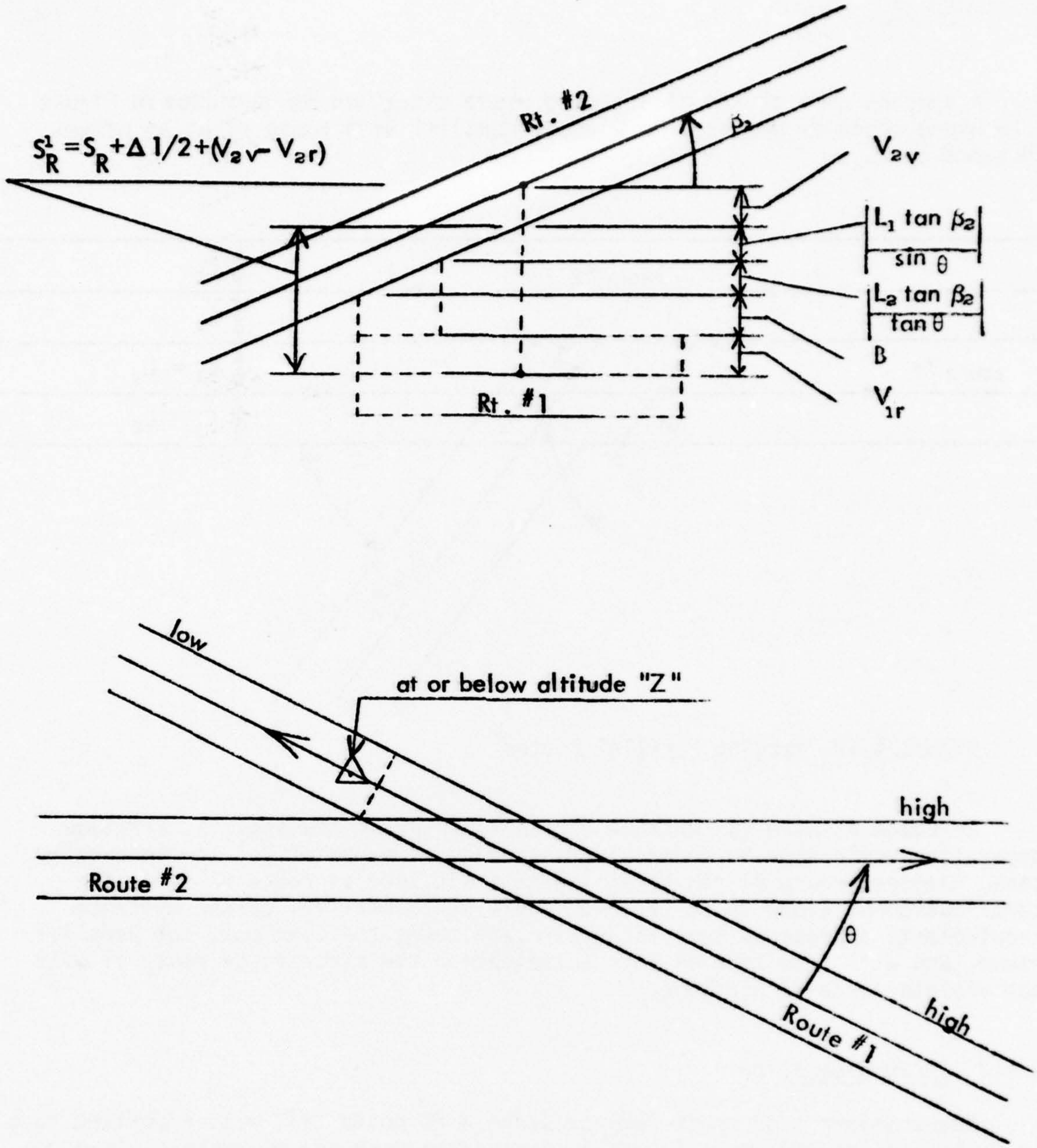


Figure A.20 2D and 3D Crossing

where $2V_1$ and $2V_2$ are the 3 σ vertical dimensions of routes #1 and #2 respectively, B is a "buffer" of 300 ft., and,

$$V = \sqrt{(3\sigma_v)^2 + (3\sigma_{at}\tan\beta)^2} \qquad \text{Equation (23)}$$

In the terminal area, the suggested value for $3\sigma_V$, the error due to altimetry, VNAV equipment, and flight technical error, is ± 350 ft. If a system error budget is assumed which results in a 2σ cross track error of ± 2 nm and which includes a 2σ cross track FTE of 1.0 nm, the 3σ along track error reflected into the vertical will be 274 ft. per degree of β.

Then,

$$V = \sqrt{(350)^2 + (274\beta)^2} \qquad \text{Equation (24)}$$

where β is in degrees.

The vertical separation between a 2D and 3D route in the terminal area as illustrated in Figure A.20 may then be derived from (22) with $\beta_1 = 0$, and $V_{1r} = 320$ ft. (The vertical dimension of a 2D route is slightly less than that of a 3D route with β=0, due to VNAV equipment error in the latter). The location of the altitude restriction point on route #1 may then be derived from Equation (20).

A.5.4 2D vs 3D Altitude Separation

The amount of altitude separation required between crossing routes is a function of crossing angle and vertical path angles for 3D routes and may be several thousand feet. 2D crossing routes require only 1000 feet vertical separation, but the altitude restriction points may be many miles from the intersection along the routes. Consider the 2D crossing routes depicted in Figure A.21. In case I through IV and in cases V through VIII the altitude restriction requirements are the same. Altitude separation must be maintained over the entire area of the intersection of the routes, plus a distance equal to the longitudinal uncertainty of position on each route. For acute intersection angles (θ small) an "overlap" of the routes for separation purposes may exist over a horizontal distance of 30 miles or more. The distance from the route intersection to the required altitude restriction point $L_x = L_y$, is given in Table A.3 for several values of route intersection angle θ for route widths of ± 2 nm. Note that the "overlap" given is Table A.3 is made up of the distance due to the intersection of the route widths at the crossing angle θ plus a constant 2 nm longitudinal uncertainty of position.

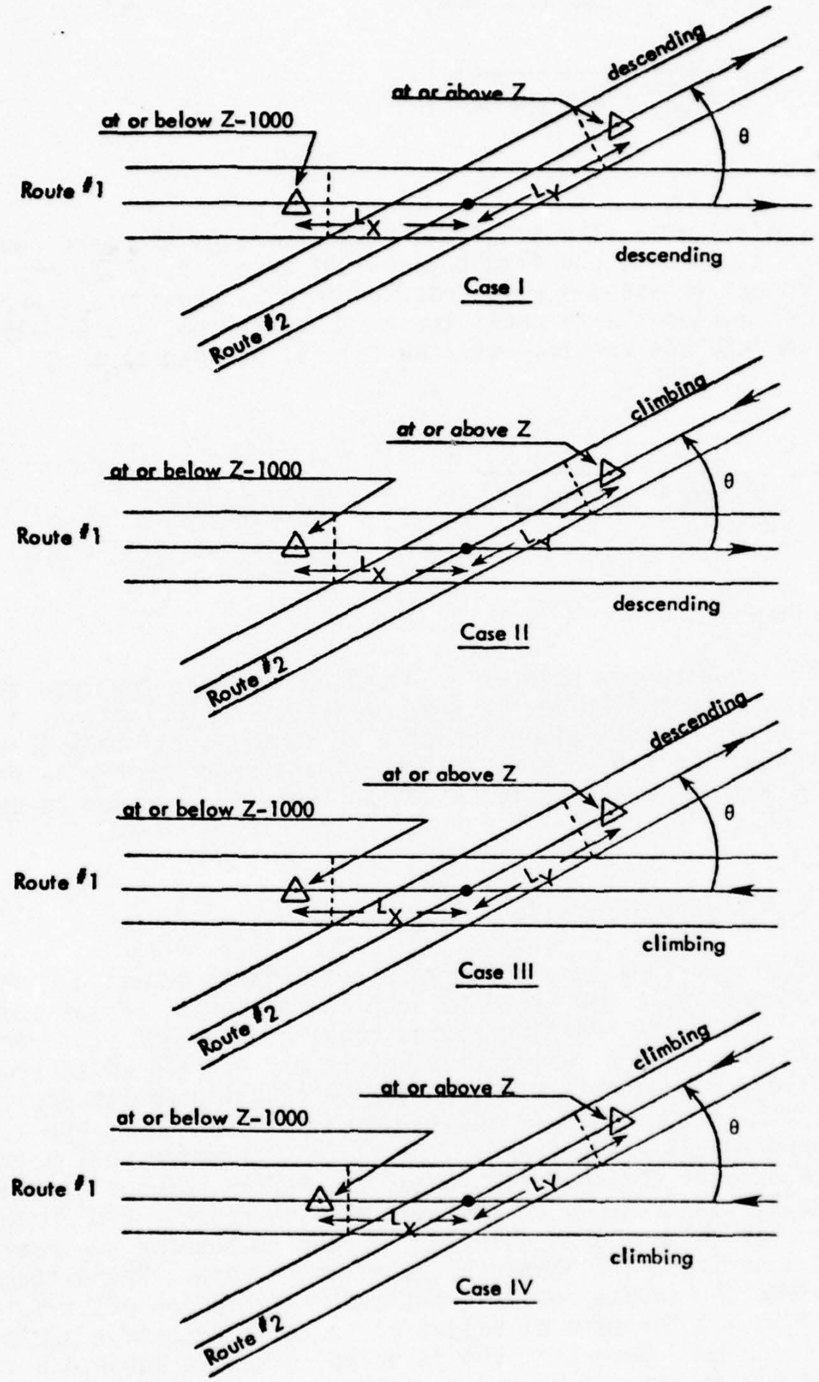


Figure A.21 2D Crossing Route Altitude Restrictions

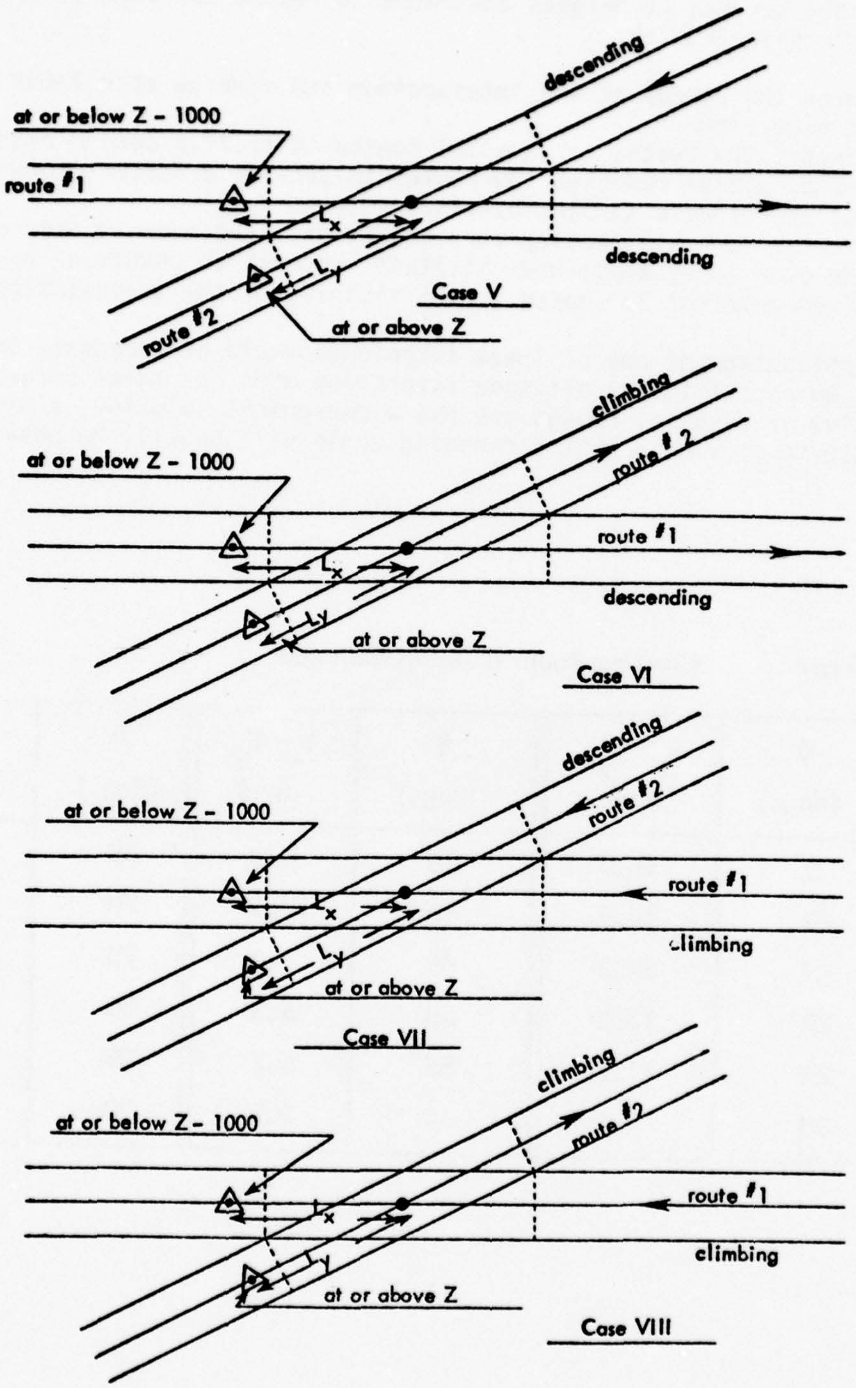


Figure A.21 (cont.) 2D Crossing Route Altitude Restrictions

There are several techniques available to reduce the effects of the overlap of crossing routes:

1) merge the routes at the intersection and demerge at a later point if necessary
2) convert the routes to parallel routes if traffic demand requires both routes and/or redesign the routes to provide a larger crossing angle, and therefore a smaller overlap distance
3) provide for satisfactory vertical flight envelopes in the region of the overlap by additional altitude restriction points or by specifying fixed gradient 3D routes in the vicinity of the intersection

The application of one of these techniques would be necessary only in the rare cases where sufficient altitude separation does not exist naturally. If merged routes or parallel routes are not a convenient solution, a minor shifting of one route to provide a better crossing angle will usually be possible.

Table A.3 Crossing Route Overlap Distance

θ (deg.)	$L_x = L_y$ (nm)	θ (deg.)	$L_x = L_y$ (nm)	θ (deg.)	$L_x = L_y$ (nm)
5	48.0	35	8.3	65	5.1
10	24.9	40	7.5	70	4.8
15	17.2	45	6.8	75	4.6
20	13.3	50	6.3	80	4.4
25	11.0	55	5.8	85	4.2
30	9.5	60	5.5	90	4.0

Table A.4 Additional Route Length for Increased Crossing Angles

θ (deg.)	$2L_x$ (nm)	max $\Delta(2L_x)$ to attain crossing angle of:	
		45°	60°
10	49.8	3.4	4.8
20	26.6	2.4	3.9
30	19.0	1.6	3.0
40	15.0	0.7	2.0
50	12.6	—	1.0

Table A.4 gives the maximum additional route length which would have to be added to one route when redesigning that route to increase the crossing angle with another route to a more acceptable value (i.e., 45°-60°). In the design of seven terminal areas it was found that crossing angles were not a constraint. Minimum crossing angles were usually on the order of 30° between arrival and departure routes, and this angle did not produce vertical separation problems. Arrival routes to multiple airports, which have the potential for small crossing angles, usually are common and are demerged at the appropriate point. Conversely, departure routes are merged prior to the departure way-points. An increase in route length to improve crossing angles would be a very rare occurrence and would seldom involve addition of the maximum distance.

The remainder of this subsection addresses the vertical separation required between the centers of crossing fixed gradient 3D (VNAV) routes as compared with the vertical distance between the "effective" centerlines, in the vertical plane, of crossing 2D routes where the vertical path angle (VPA), or "fixed gradient", of the "effective" centerlines are determined by the constraints of altitude restriction points. The latter case is referred to as "2D vertical separation" for convenience in the discussion that follows.

The difference between 2D and 3D vertical separation is illustrated in Figure A.22. The altitude Z is defined as the midpoint altitude between the centerlines of two crossing routes. S_V is the vertical separation between 3D routes at the intersection and S_R is defined as the vertical separation which would be required between two 3D routes if 2D (blocked altitude) separation were to be provided instead of 3D separation. Figure A.22a illustrates (fixed gradient 3D) crossing routes. Figures A.22b illustrates the blocked airspace and altitude restriction points for 2D separation. The distance of the altitude restriction points on each route from the intersection of the routes may be derived from Table A.3. Vertical separation for 3D crossing routes is given by Equation (22). The vertical distance between the "effective" centerlines of crossing 2D routes, as illustrated in Figure A.22b is given by:

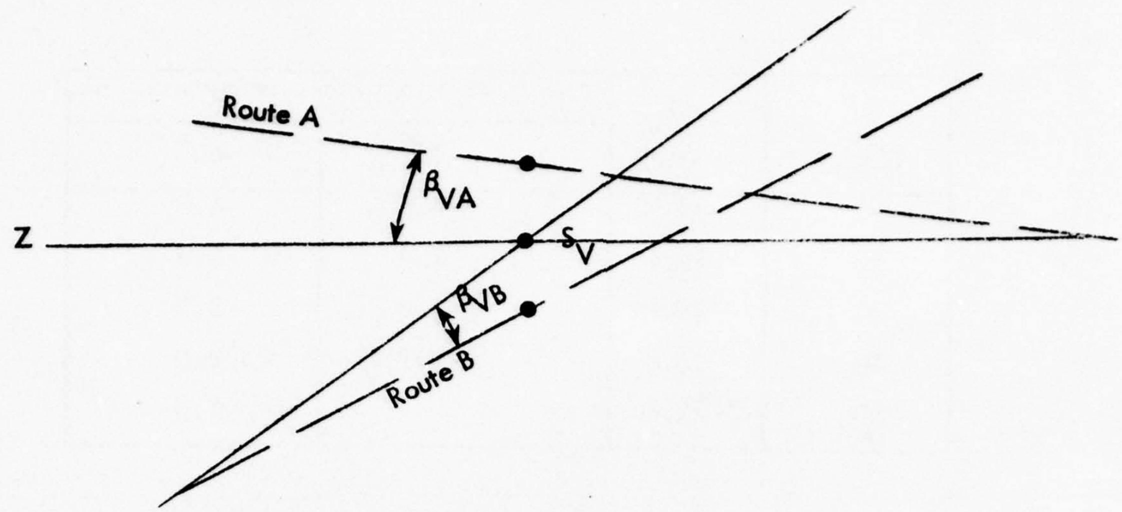


Figure A.22a Vertical Separation of 3D Routes

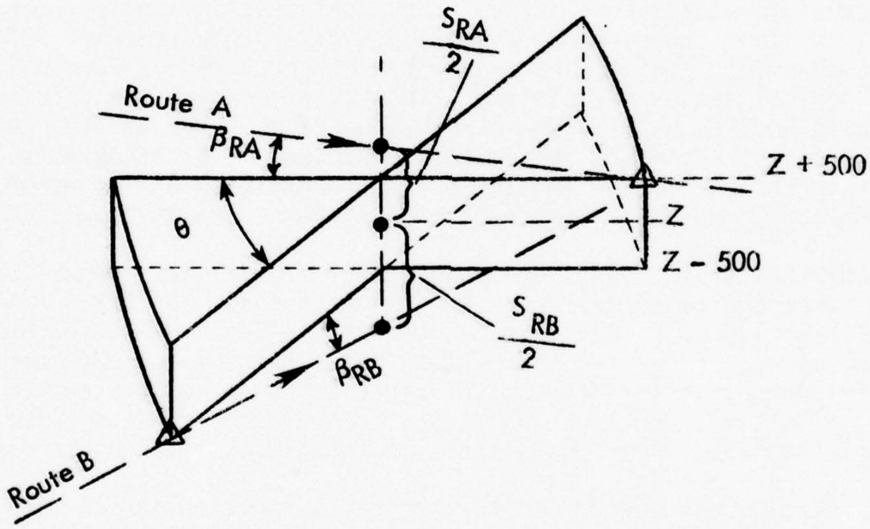


Figure A.22b 2D Separation

Figure A.22 2D and 3D Vertical Separation

$$S_R = \frac{S_{RA}}{2} + \frac{S_{RB}}{2} = L_x \tan \beta_{RA} + L_y \tan \beta_{RB} + 1000 \qquad \text{Equation (25)}$$

Figure A.23 gives the vertical separation requirements for 3D intersecting routes, with a constant route width of ± 2 nm as a function of crossing angle and vertical path angles. The 2D "separation" as defined above is also given. It should be emphasized that 2D vertical separation can always be reduced to 1000 ft. by shifting one route horizontally to improve the crossing angle and/or allowing the effective maximum vertical path angle to increase on one side of the altitude restriction point and to decrease on the other side. Figure A.23 applies to the case where it is desired to maintain a 3D ceiling or floor (or minimum or maximum average 2D vertical path angle) which is defined by a straight line between the waypoints defining the respective legs of the routes.

It can be seen from Figure A.23a that there is virtually no difference between 2D and 3D separation when one of the routes is level ($\beta = 0$). When the vertical path angles are equal (Figure A.23b) there is also little difference for $90° < \theta \leq 180°$ (one route climbing and one descending). When θ is less than 90°, however, 2D separation increases with descreasing crossing angle, while 3D separation approaches the minimum value required for "stacked" VNAV routes.

In the cases where the vertical path angles are different and neither is equal to zero (Figure A.23c) there is also little difference when θ is greater than 90°, although the difference increases at 90° as the difference between vertical path angles increases.

The majority of crossing route situations encountered in the terminal area RNAV design involve the climbing/descending case ($90°<\theta<180°$) where there is little, if any, advantage to fixed gradient 3D routes in decreasing vertical separation. The climb-climb and descent-descent cases ($\theta<90°$) for small crossing angles occur very rarely, and are associated with multiple airport arrivals and departures in a metroplex terminal area. In these cases the minimum vertical distance between the routes is already several thousand feet because of the large difference in path length from the intersection of the route to the respective airports.

Use of a fixed gradient VNAV route to provide vertical separation for a crossing route would sometimes require an additional waypoint. As indicated in Figure A.24a the VNAV route must start at an altitude equal to or greater than A if the crossing waypoint C is to be eliminated. Similarly, in Figure A.24b the VNAV route must start at an altitude equal to or less than A, and in Figure A.24c the VNAV route must start at an altitude between A and A' if waypoint C or D is to be eliminated.

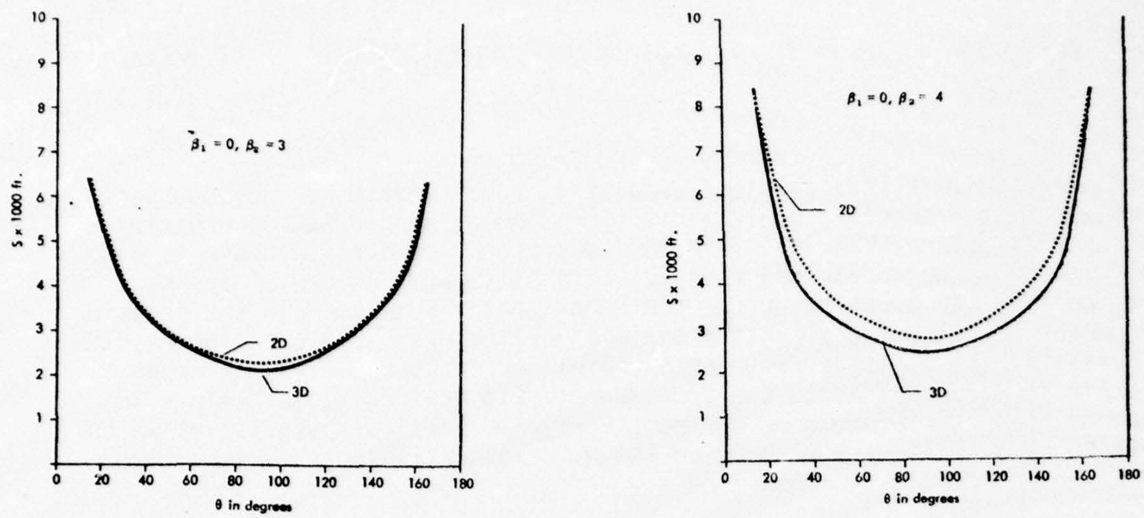


Figure A.23a

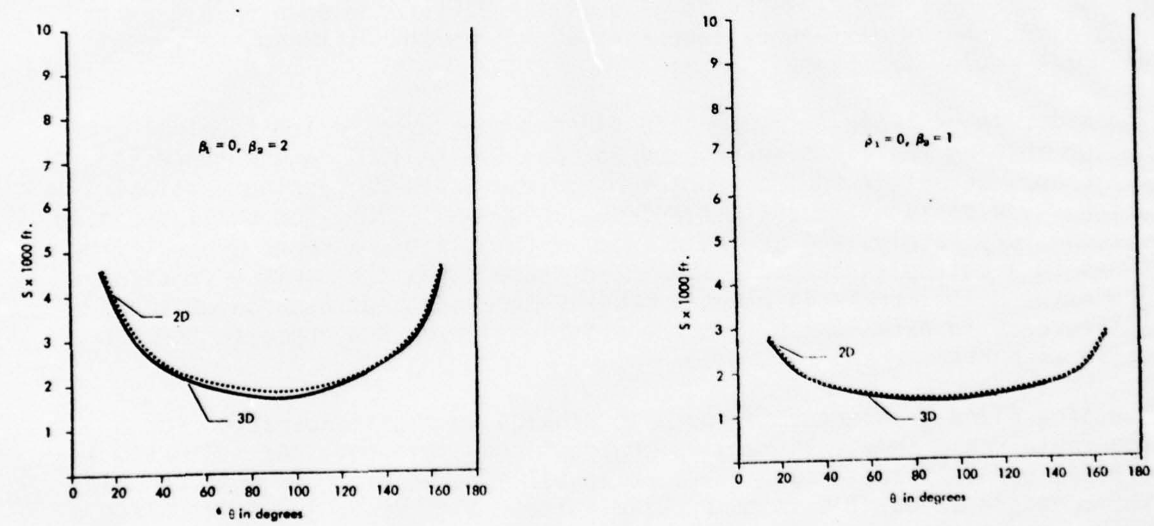
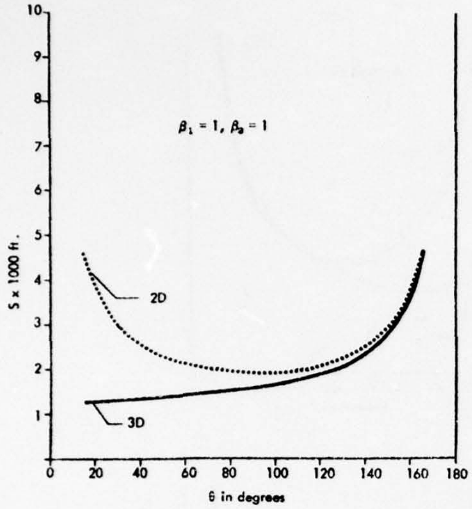


Figure A.23 2D vs 3D Separation Requirements



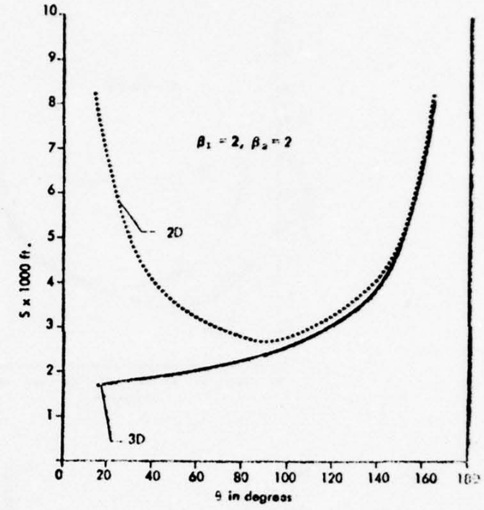
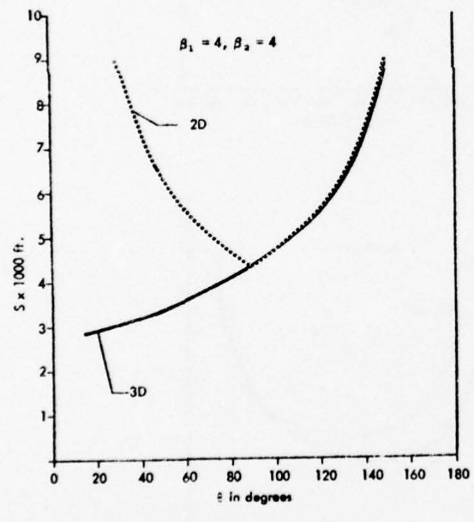


Figure A.23b



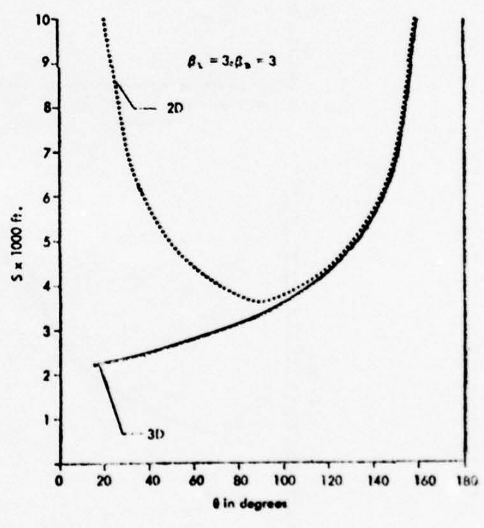


Figure A.23(continued) 2D vs 3D Separation Requirements

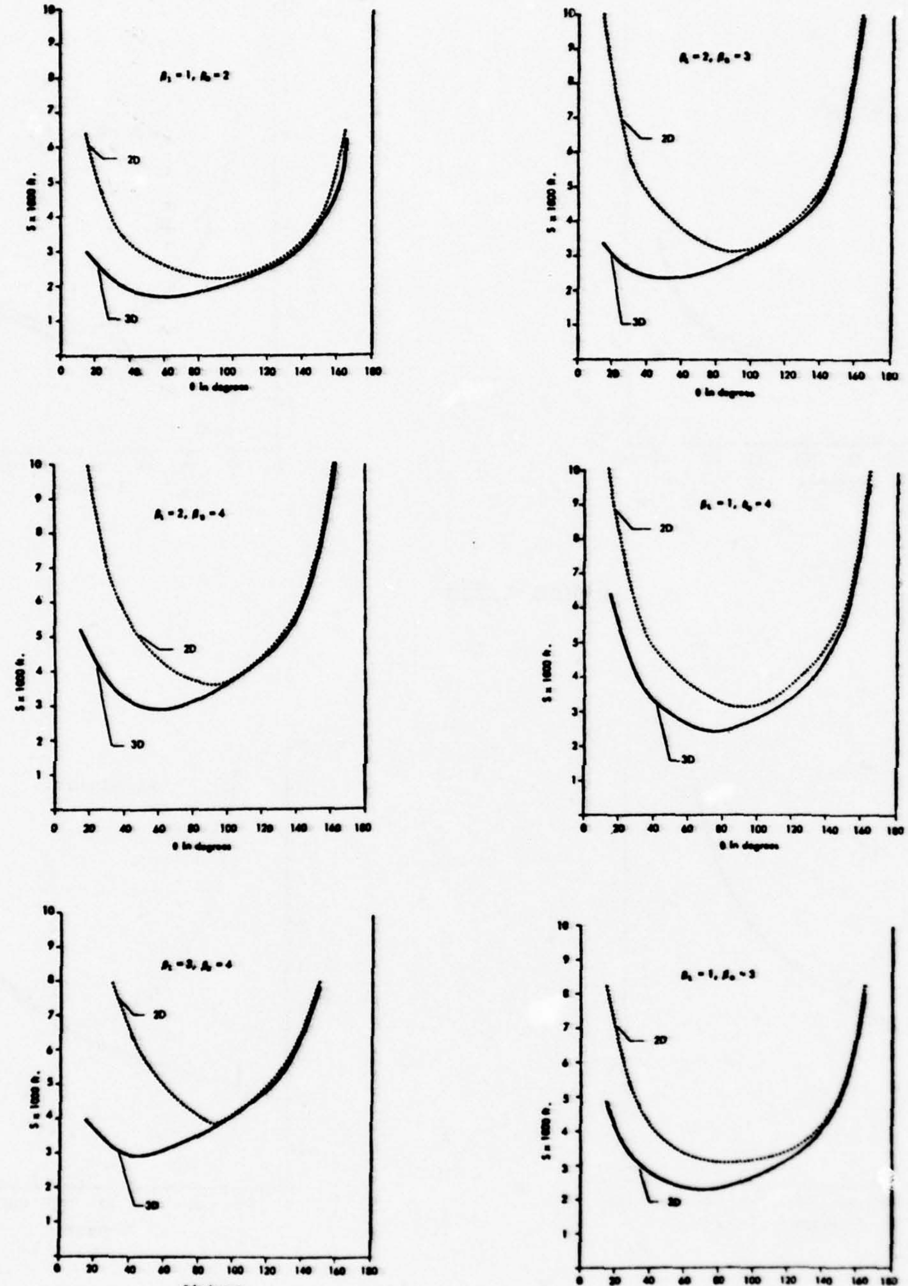


Figure A.23c

Figure A.23 (cont.) 2D vs. 3D Separation Requirements

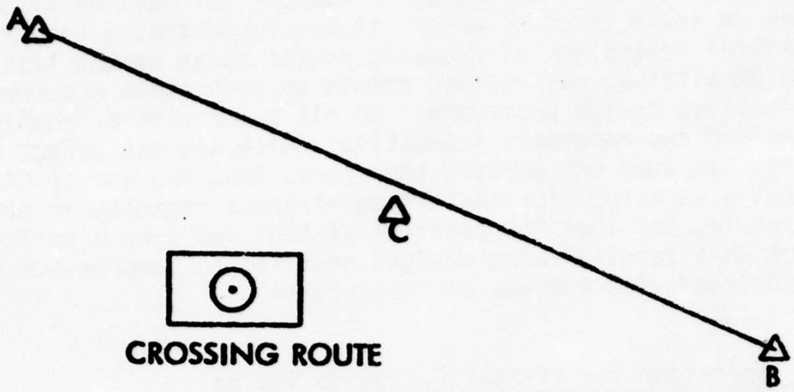


Figure A.24a

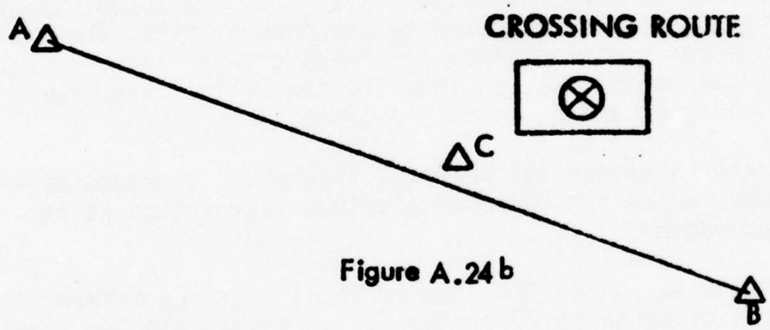


Figure A.24b

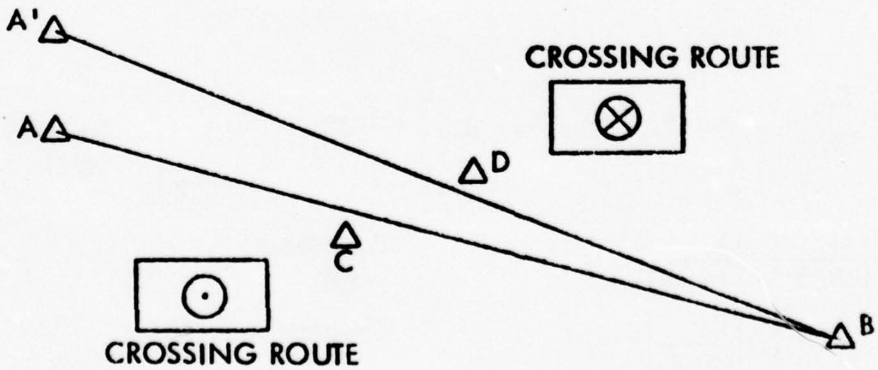


Figure A.24c

Figure A.24 Waypoint Requirements for Crossing Fixed Gradient VNAV Routes

In the process of creating more than 40 designs for various airports and traffic flows in seven terminal areas, it was found that a requirement for reducing vertical separation of crossing routes to an amount less than that provided by 2D altitude restriction points on each route occurred very rarely in the iterative design procedure. In all cases a minor realignment of one route provided the necessary separation, which did not affect user economic benefits. It does not appear, therefore, that the use of fixed gradient VNAV routes as a tool for increasing airspace capacity is either required or desirable, and that the substantial fuel and time benefits available through RNAV terminal area designs need not be compromised by the complexities associated with the use of such routes.

A.5.5 Vertical Separation for Pilot-Selected 3D Routes

Figure A.23 shows a comparison of the required separation between crossing VNAV routes and the vertical distance between the "effective" centerline of crossing 2D routes. The "effective" gradient of a 2D route may also be defined as a pilot-selected fixed gradient to or from the 2D altitude restriction point. It can be seen from Figure A.23 that the actual separation of pilot-selected 3D gradient, as indicated by the dashed lines, when passing through the 2D altitude restriction points is always greater than, or equal to, the required vertical separation, as shown by the solid lines, for combinations of vertical path angles up to 4 degrees.

This section further analyzes the vertical separation provided between pilot-selected 3D routes which are based on altitude restriction points established for 2D separation.

In Section A.5.4, it was shown that the vertical distance between the "effective" centerlines of crossing 2D routes (or of pilot-selected gradients), is given by the following equation:

$$S_R = \frac{S_{RA}}{2} + \frac{S_{RB}}{2} = L_x \left|\tan \beta_{RA}\right| + L_y \left|\tan \beta_{RB}\right| + 1000 \qquad \text{Equation (25)}$$

where

$$L_x = \left|\frac{L_2}{\sin\theta}\right| + \left|\frac{L_1}{\tan\theta}\right| + L_1 \qquad \text{Equation (20)}$$

$$L_y = \left|\frac{L_1}{\sin\theta}\right| + \left|\frac{L_2}{\tan\theta}\right| + L_2 \qquad \text{Equation (21)}$$

if both aircraft are using a fixed gradient for guidance, then $\beta_1 = \beta_{RA}$ and $\beta_2 = \beta_{RB}$, and the required vertical separation is (from Section A.3):

$$Sv = V_1 + V_2 + B + L_1 \left|\frac{\tan\beta_2 - \cos\theta\tan\beta_1}{\sin\theta}\right| + L_2 \left|\frac{\tan\beta_1 - \cos\theta\tan\beta_2}{\sin\theta}\right| \qquad \text{Equation (10)}$$

Combining Equations (20), (21), and (25) and setting $S_R = \Delta Hv$, the actual vertical separation of the centerline of the fixed gradient 3D routes will be given by:

$$\begin{aligned}\Delta Hv = {} & L_1 \left|\tan\beta_1\right| + L_2 \left|\tan\beta_2\right| + 1000 \\ & + L_1\left\{\frac{\left|\tan\beta_1\right| \left|\cos\theta\right| + \left|\tan\beta_2\right|}{\left|\sin\theta\right|}\right\} \\ & + L_2\left\{\frac{\left|\tan\beta_2\right| \left|\cos\theta\right| + \left|\tan\beta_1\right|}{\left|\sin\theta\right|}\right\}\end{aligned} \qquad \text{Equation (26)}$$

by definition, β_1 and β_2 are positive; therefore, for $0 \leq \theta \leq \frac{\pi}{2}$,

$$\frac{\left|\tan\beta_2\cos\theta\right| + \left|\tan\beta_1\right|}{\left|\sin\theta\right|} \geq \left|\frac{\tan\beta_1 - \cos\theta\tan\beta_2}{\sin\theta}\right|$$

and

$$\frac{\left|\tan\beta_1\cos\theta\right| + \left|\tan\beta_2\right|}{\left|\sin\theta\right|} \geq \left|\frac{\tan\beta_2 - \cos\theta\tan\beta_1}{\sin\theta}\right|$$

also, for $\frac{\pi}{2} \leq \theta \leq \pi$,

$$\frac{\left|\tan\beta_2\cos\theta\right| + \left|\tan\beta_1\right|}{\left|\sin\theta\right|} = \left|\frac{\tan\beta_1 - \cos\theta\tan\beta_2}{\sin\theta}\right|$$

and

$$\frac{\left|\tan\beta_1\cos\theta\right| + \left|\tan\beta_2\right|}{\left|\sin\theta\right|} = \left|\frac{\tan\beta_2 - \cos\theta\tan\beta_1}{\sin\theta}\right|$$

By comparing equation (10) with equation (26), it can be seen that ΔHv will always be equal to or larger than Sv if:

$$L_1 |\tan \beta_1| + L_2 |\tan \beta_2| + 1000 \geq V_1 + V_2 + B$$

Let $\Delta S = \Delta Hv - Sv$ and $B = 300$ ft. (ref. Section A.3)

then $\Delta S = L_1 |\tan \beta_1| + L_2 |\tan \beta_2| + 700 - V_1 - V_2$ (Equation (27)

Figure A.25 is a plot of ΔS_{min} vs β_1 and β_2 for the following conditions (reference Equation (24)):

$$L_1 = L_2 = 2 \text{ nm}$$

$$V_1 = \sqrt{(350)^2 + (274\ \beta_1)^2}$$

$$V_2 = \sqrt{(350)^2 + (274\ \beta_2)^2}$$

where β_1 and β_2 are in degrees

The separation buffer shown in Figure A.25 is the minimum buffer that will exist, independent of the crossing angle of the routes for $0 \leq \theta \leq \frac{\pi}{2}$, and is the actual buffer that will exist for $\frac{\pi}{2} \leq \theta \leq \pi$. If both routes are climbing or both routes are descending $(0 \leq \theta \leq \frac{\pi}{2})$ and $\theta \leq 87°$ the separation buffer will always be greater than zero for combinations of $0 \leq \beta_1 \leq 6°$ and $0 \leq \beta_2 \leq 6°$. If one route is climbing and the other route descending $(\frac{\pi}{2} \leq \theta \leq \pi)$, the altitude restriction points must be placed 0.2 nm further from the route intersection to insure vertical separation between pilot-selected combinations of fixed gradient routes up to 6 degrees.

A.6 SYSTEM ERROR CONTOURS

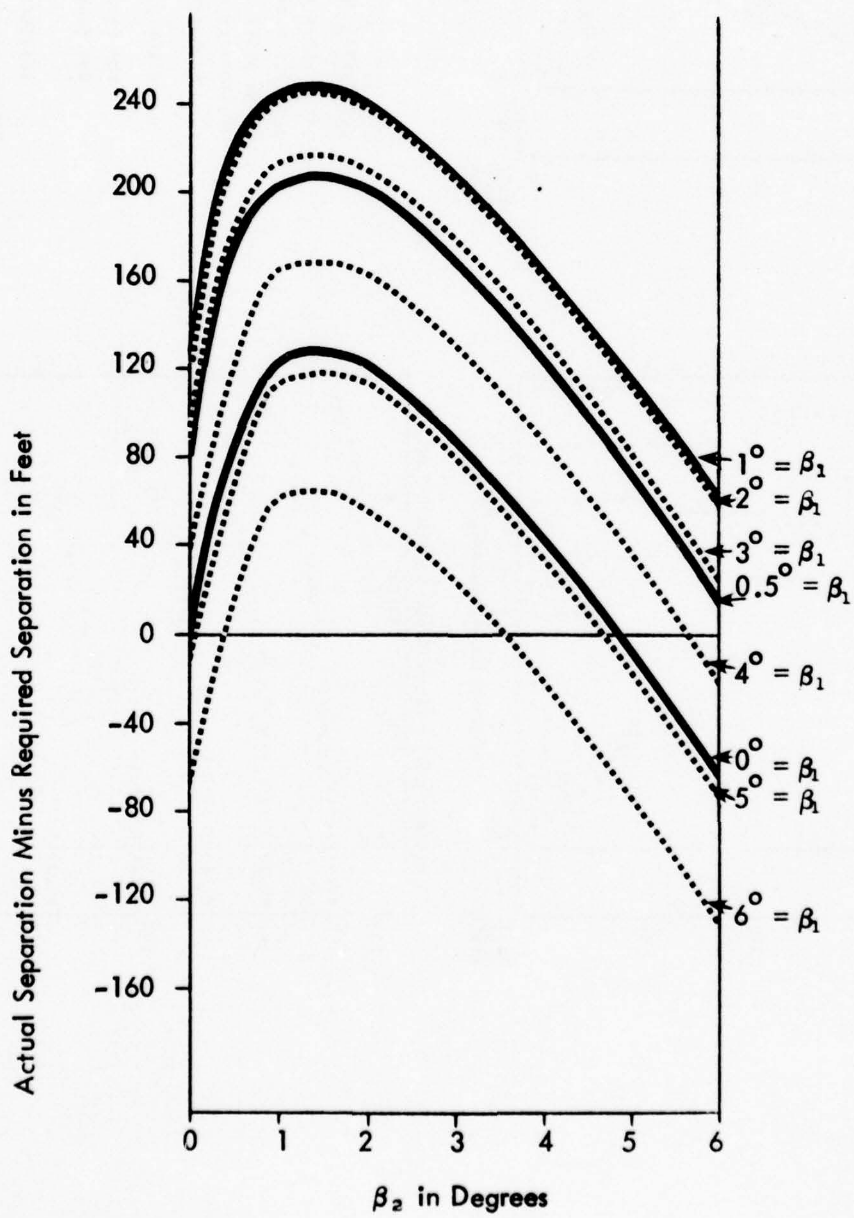
An accuracy analysis of VNAV system errors was performed for three different time periods and three airspace areas. The three time periods correspond to those in the Task Force Report [1], namely 1972-77, 1977-82 and post-1982. The three airspace areas considered were approach, terminal area and enroute.

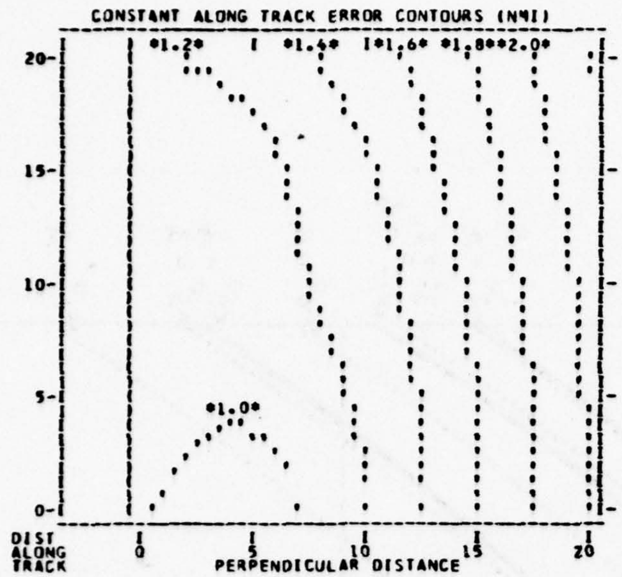
Contours of constant system error were plotted for along track errors, cross track errors and vertical errors. In order to include the effect of along track errors propagated into the vertical direction a vertical path angle of 3° was assumed. Three sigma (3σ) error levels were used throughout the analysis. These contours are shown in Figures A.26 through A.34.

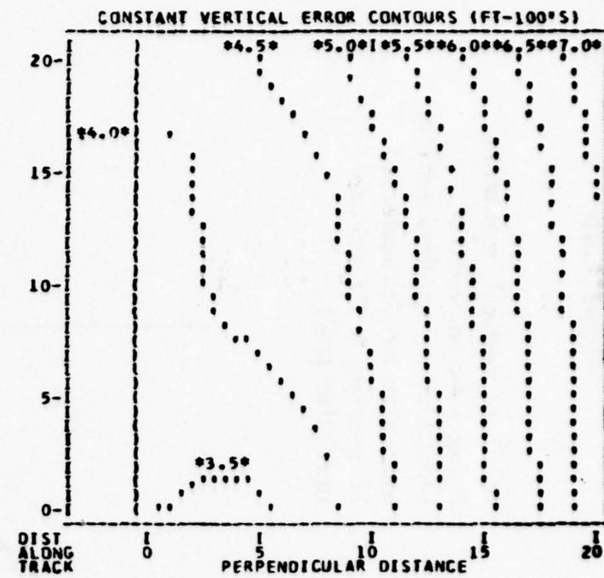
Since these error contours are often associated with route widths and heights, these contours provide indications of potential route reduction through the use of improved navigation systems for the 1977 and 1982 time periods.

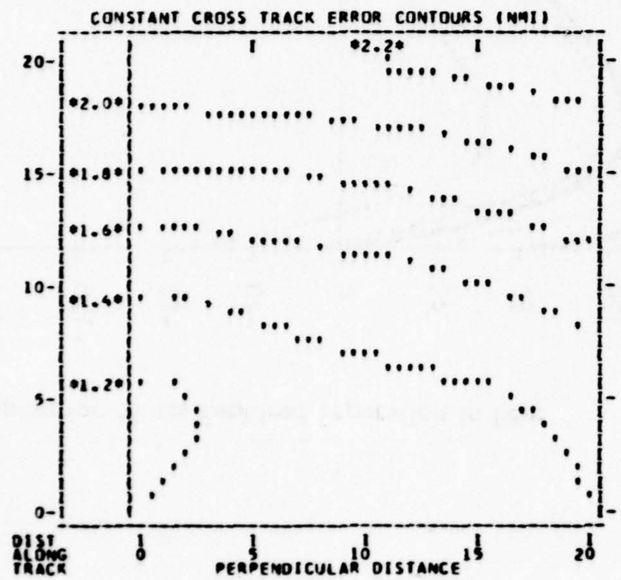
Figure A.25

Minimum Vertical Separation Buffer - Actual vertical separation vs, required vertical separation for pilot-selected 3D gradient to 2D altitude restriction point.









VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1972 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE = 5000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.75 NMI
VERTICAL = 100. FT

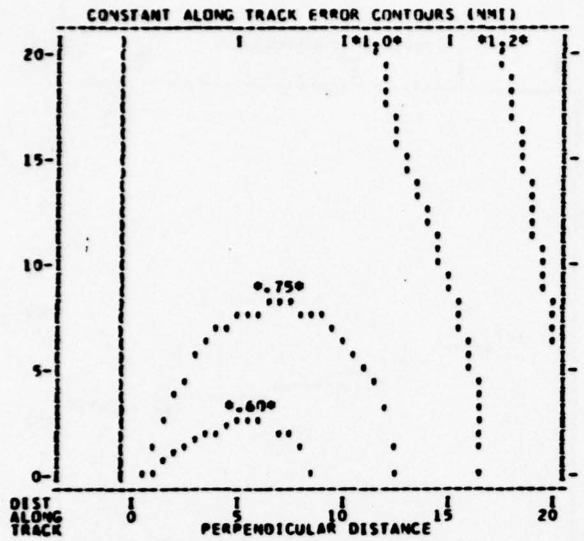
PILOT ERROR - HORIZONTAL = 0.75 NMI
VERTICAL = 150. FT

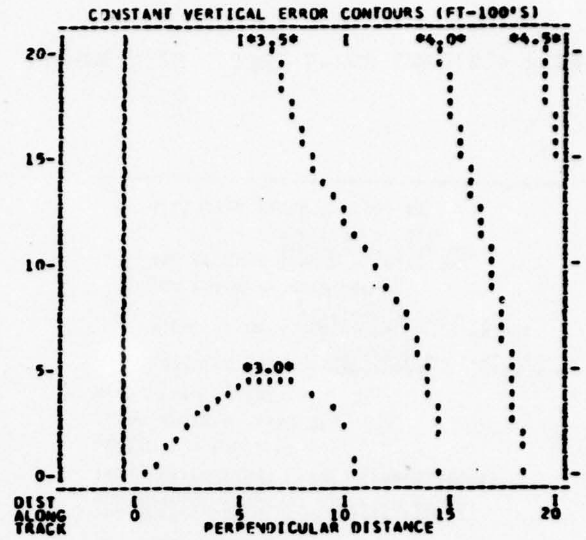
VOR ERROR = 5.33 DEG

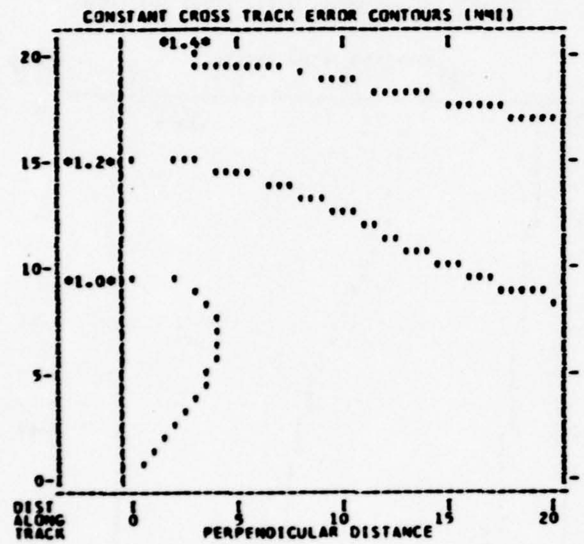
DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.75 NMI
PER CENT = 4.50

ALTIMETER ERROR = 90. FT

Figure A.26 1972 Error Levels - Final Approach







VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1977 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE = 5000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.38 NMI
VERTICAL = 100. FT

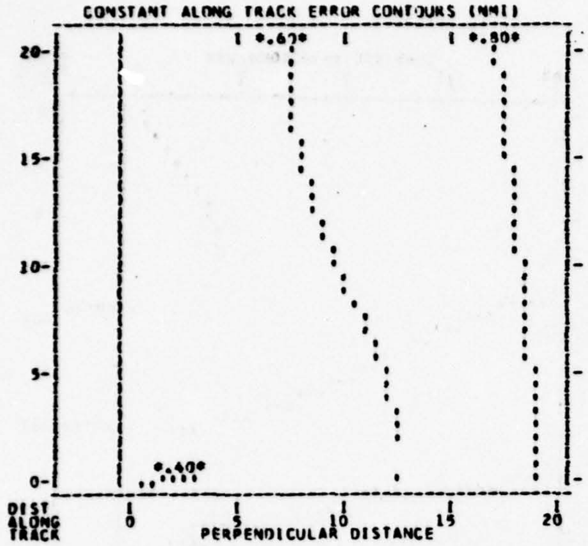
PILOT ERROR - HORIZONTAL = 0.75 NMI
VERTICAL = 150. FT

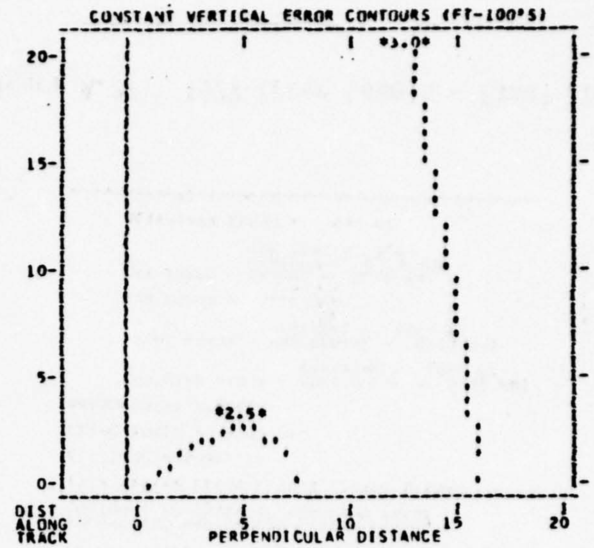
VOR ERROR = 3.19 DEG

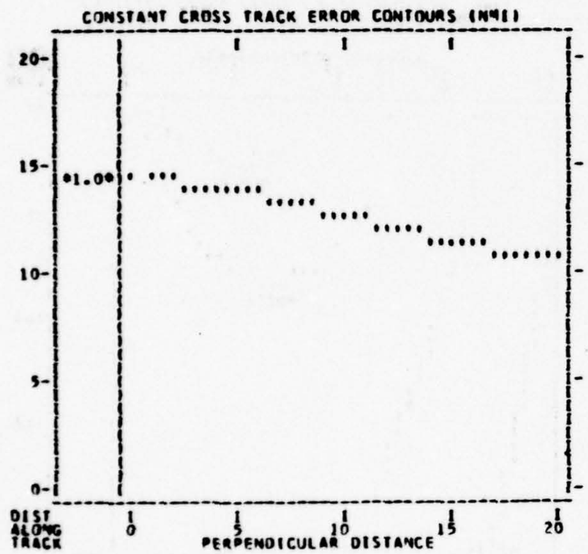
DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.75 NMI
PER CENT = 0.0

ALTIMETER ERROR = 90. FT

Figure A.27 1977 Error Levels - Final Approach







VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1982 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE = 5000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.38 NMI
VERTICAL = 100. FT

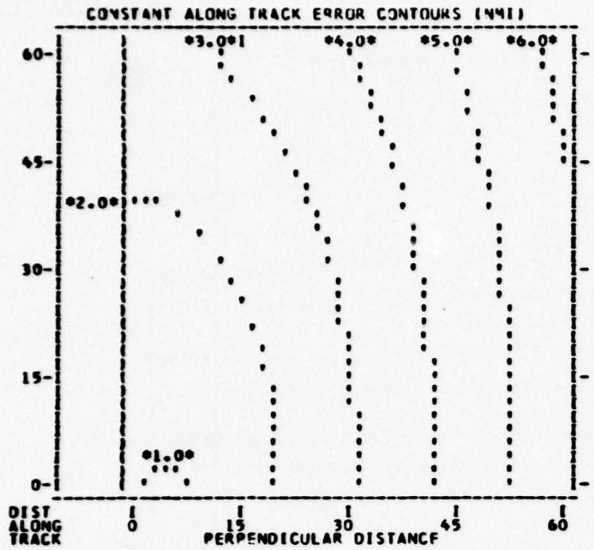
PILOT ERROR - HORIZONTAL = 0.75 NMI
VERTICAL = 150. FT

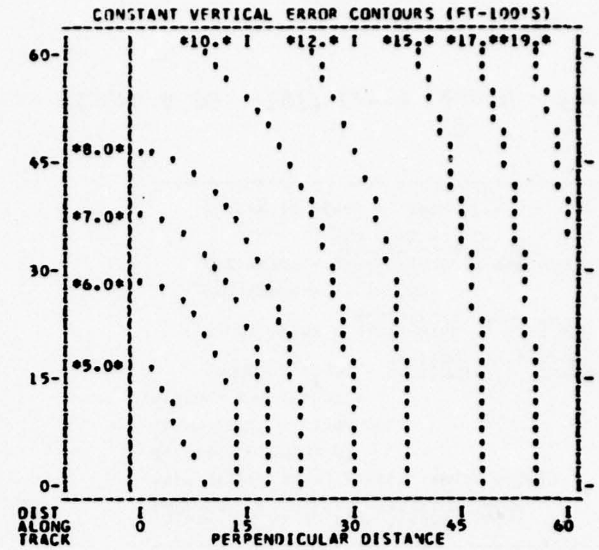
VOR ERROR = 2.12 DEG

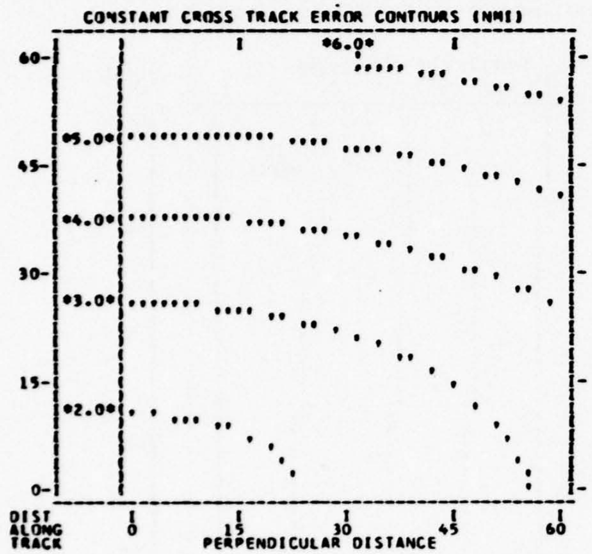
DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.38 NMI
PER CENT = 0.0

ALTIMETER ERROR = 90. FT

Figure A.28 1982 Error Levels - Final Approach







VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1972 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE =10000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.75 NMI
VERTICAL = 150. FT

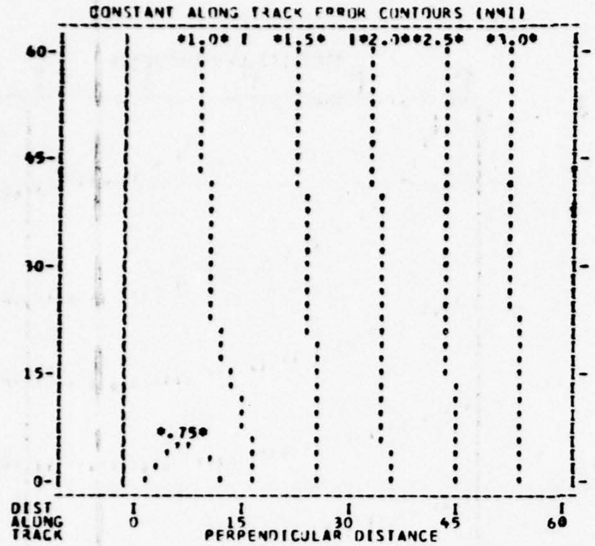
PILOT ERROR - HORIZONTAL = 1.50 NMI
VERTICAL = 250. FT

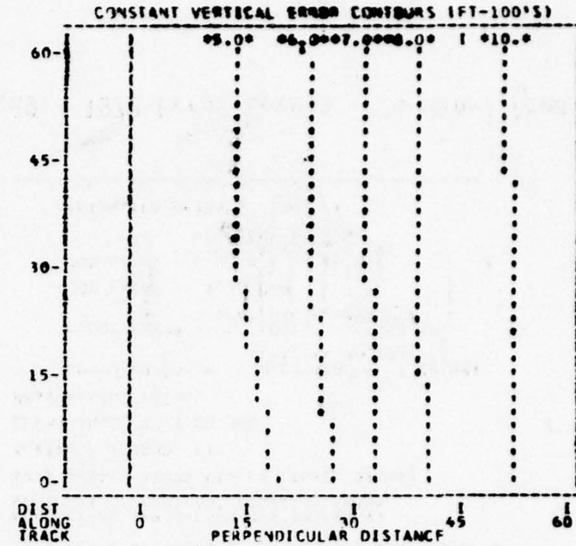
VOR ERROR = 5.33 DEG

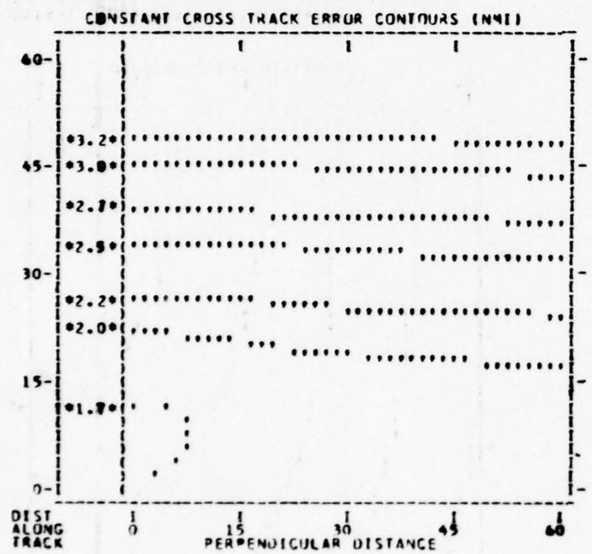
DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.75 NMI
PER CENT = 4.50

ALTIMETER ERROR = 200. FT

Figure A.29 1972 Error Levels - Terminal Area







VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1977 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE =10000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.38 NMI
VERTICAL = 150. FT

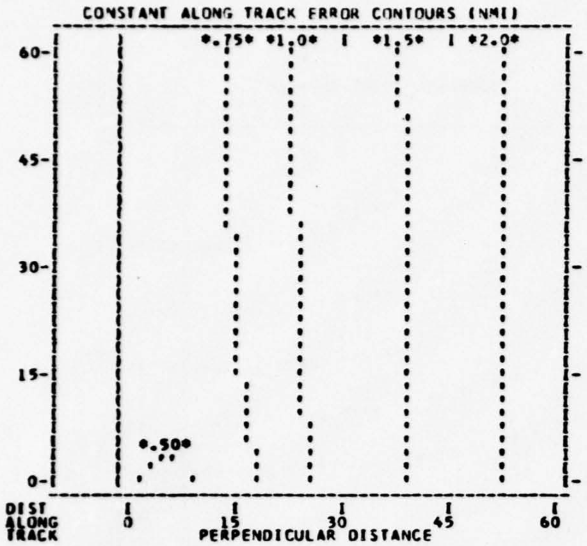
PILOT ERROR - HORIZONTAL = 1.50 NMI
VERTICAL = 250. FT

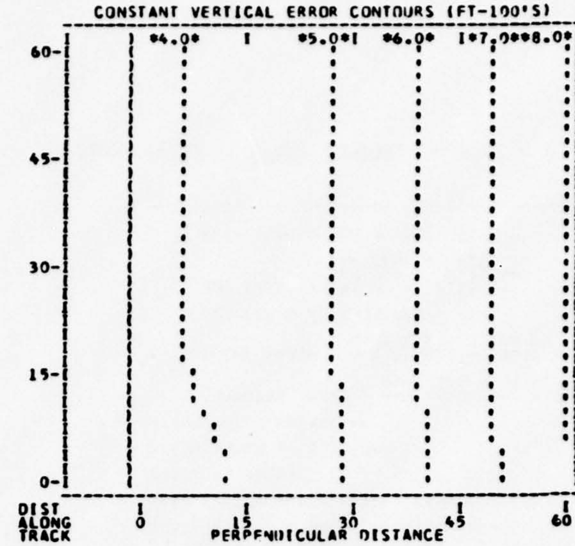
VOR ERROR = 3.18 DEG

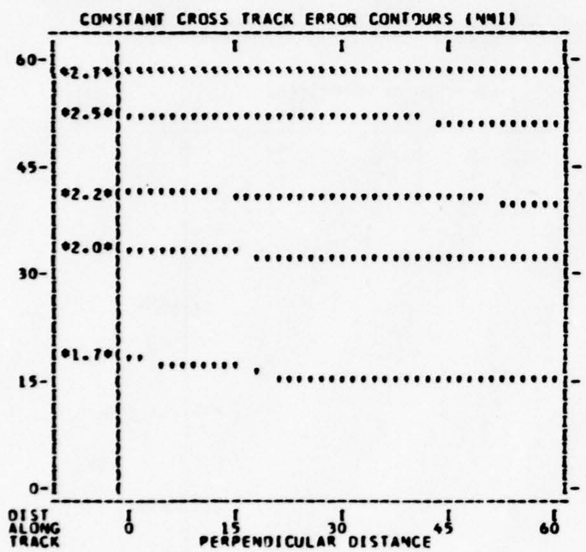
DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.75 NMI
PER CENT = 0.0

ALTIMETER ERROR = 200. FT

Figure A.30 1977 Error Levels - Terminal Area







VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1982 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE =10000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.39 NMI
VERTICAL = 150. FT

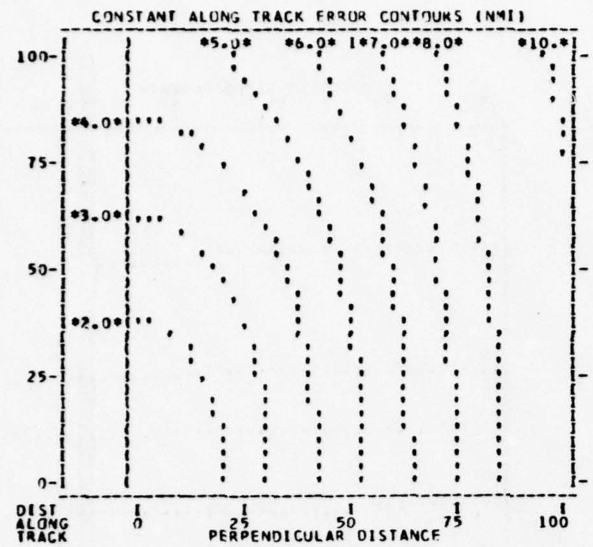
PILOT ERROR - HORIZONTAL = 1.50 NMI
VERTICAL = 250. FT

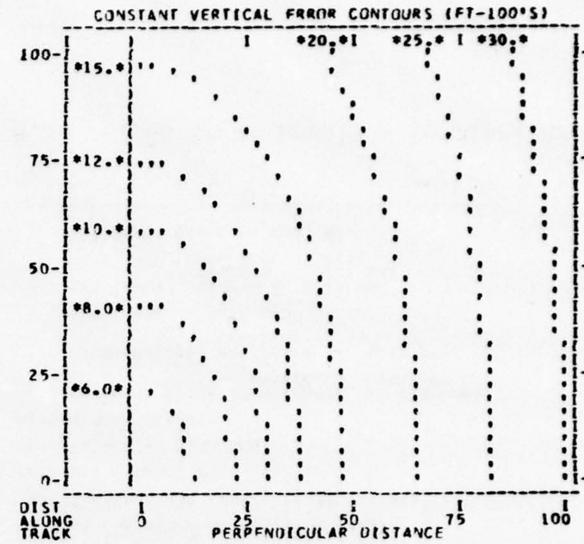
VOR ERROR = 2.12 DEG

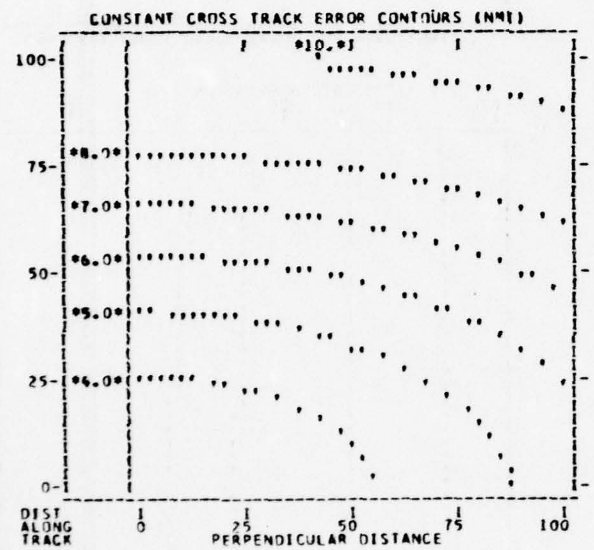
DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.39 NMI
PER CENT = 0.0

ALTIMETER ERROR = 200. FT

Figure A.31 1982 Error Levels - Terminal Area







VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1972 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE =35000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.75 NMI
VERTICAL = 220. FT

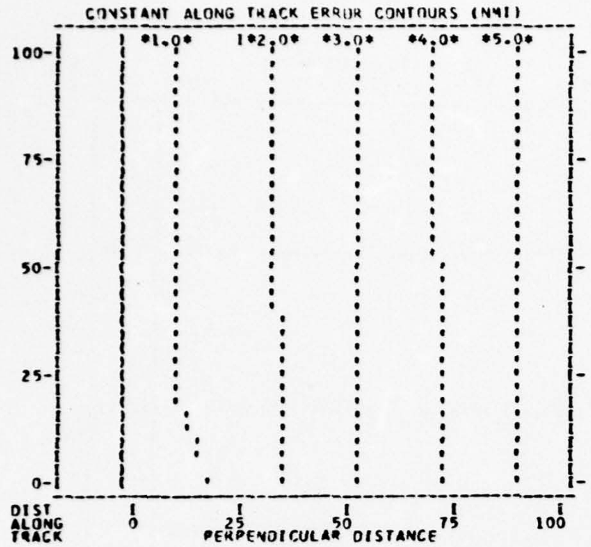
PILOT ERROR - HORIZONTAL = 3.00 NMI
VERTICAL = 250. FT

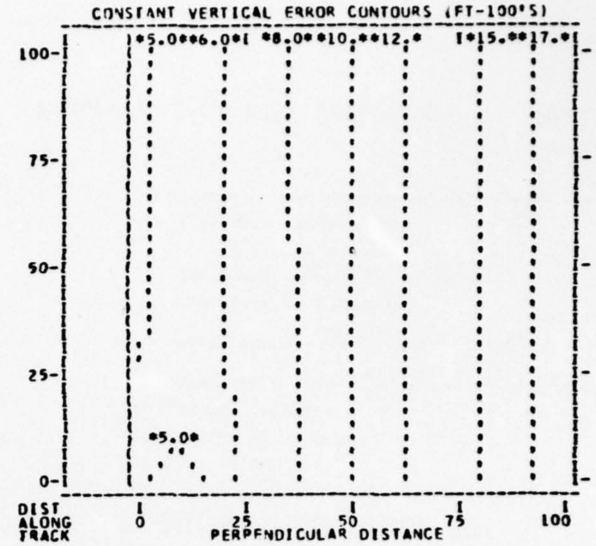
VOR ERROR = 5.33 DEG

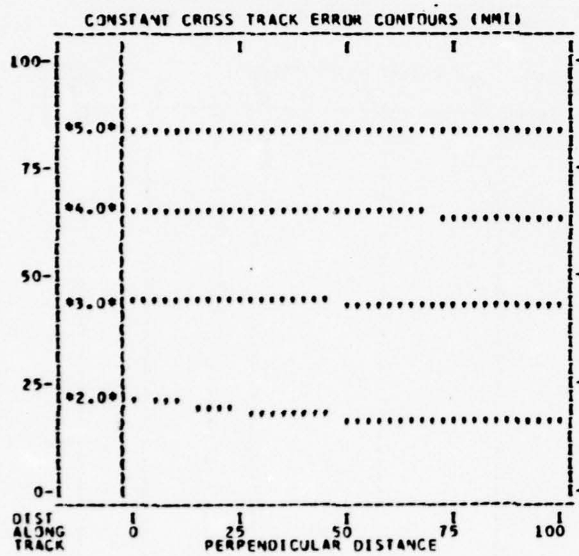
DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.75 NMI
PER CENT = 4.50

ALTIMETER ERROR = 250. FT

Figure A.32 1972 Error Levels - Enroute







VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1977 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE =35000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.38 NMI
VERTICAL = 220. FT

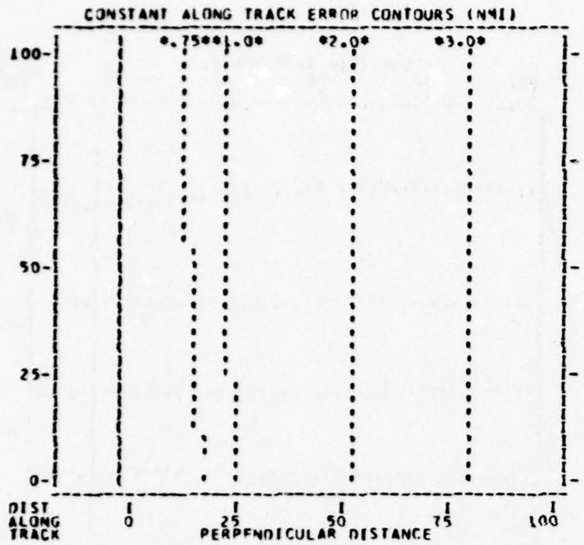
PILOT ERROR - HORIZONTAL = 1.50 NMI
VERTICAL = 250. FT

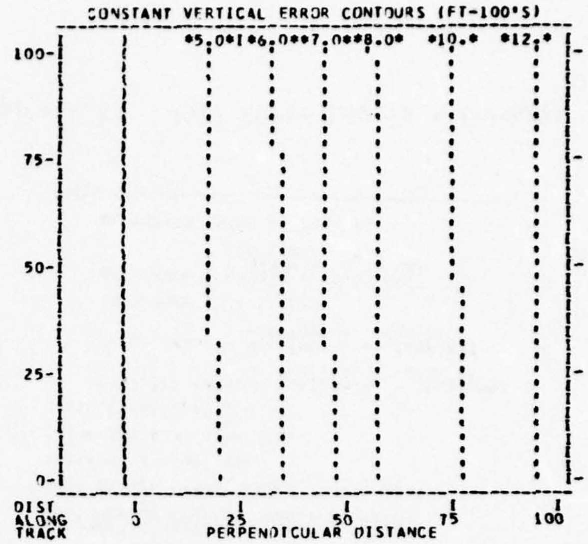
VOR ERROR = 3.18 DEG

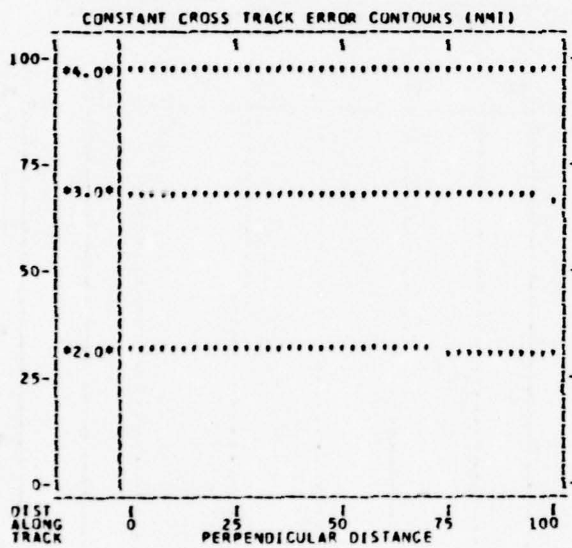
DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.75 NMI
PER CENT = 0.0

ALTIMETER ERROR = 250. FT

Figure A.33 1977 Error Levels - Enroute







VOLUMETRIC NAVIGATION SYSTEM (VNAV)
CONTOURS OF CONSTANT POSITION ERROR

1982 SYSTEM ERROR LEVELS (THREE SIGMA)

ALTITUDE =35000. FT

CLIMB ANGLE = 3.00 DEG

MEASUREMENT ERRORS -

COMPUTER ERROR - HORIZONTAL = 0.38 NMI
VERTICAL = 220. FT

PILOT ERROR - HORIZONTAL = 1.50 NMI
VERTICAL = 250. FT

VOR ERROR = 2.12 DEG

DME ERROR - GROUND = 0.15 NMI
MINIMUM = 0.38 NMI
PER CENT = 0.0

ALTIMETER ERROR = 250. FT

Figure A.34 1982 Error Levels - Enroute

APPENDIX B

NEW YORK TERMINAL AREA 3D DESIGN

This appendix contains vertical route profiles for the initial post-1982 New York terminal area. These profiles are based upon the fixed gradient approach to 3D RNAV route design. The basic route structure is presented in Section 7.3.1 of this report.

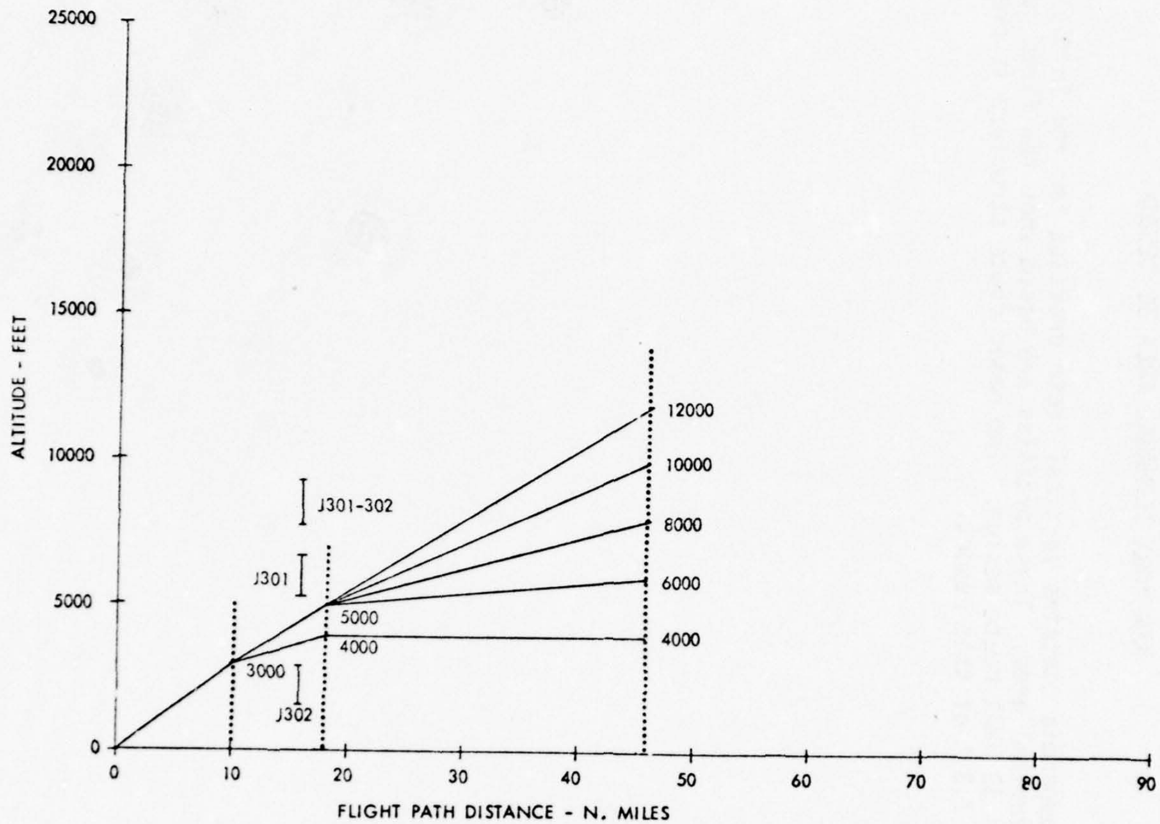


Figure B.1 Kennedy Arrival Route J201

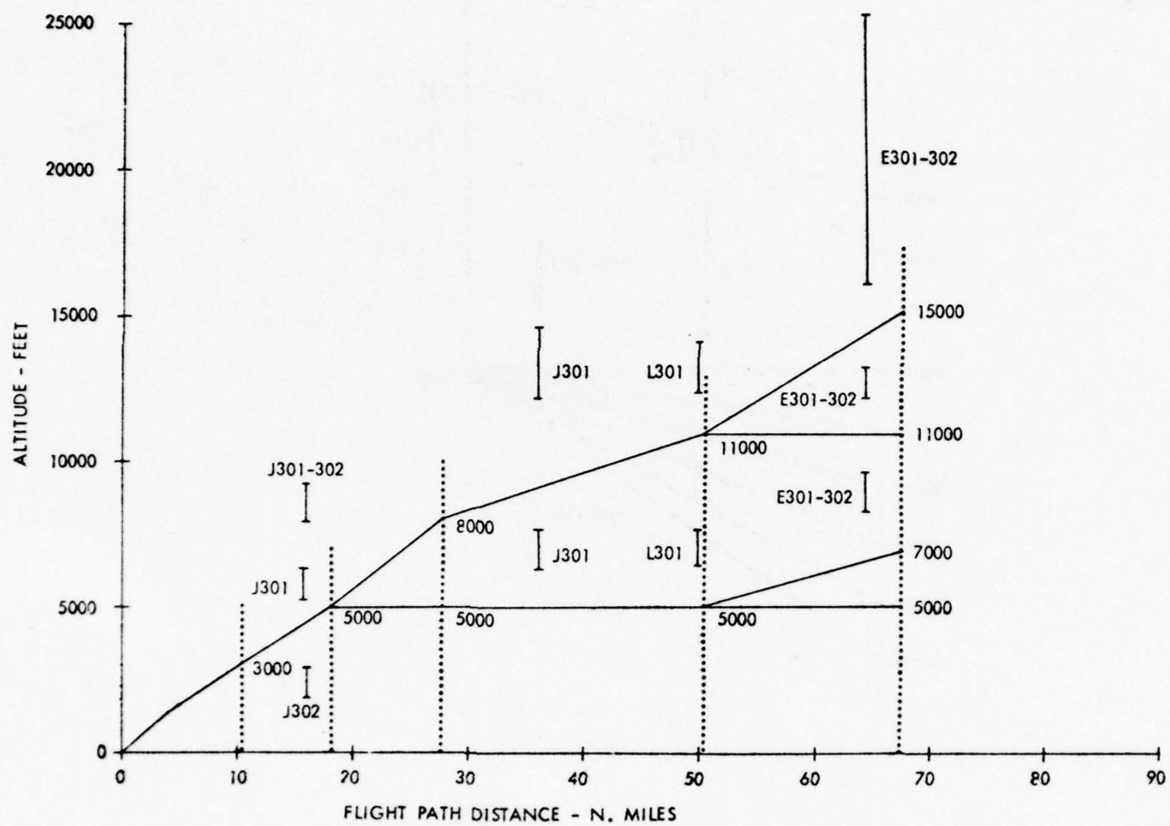


Figure B.2 Kennedy Arrival Route J202

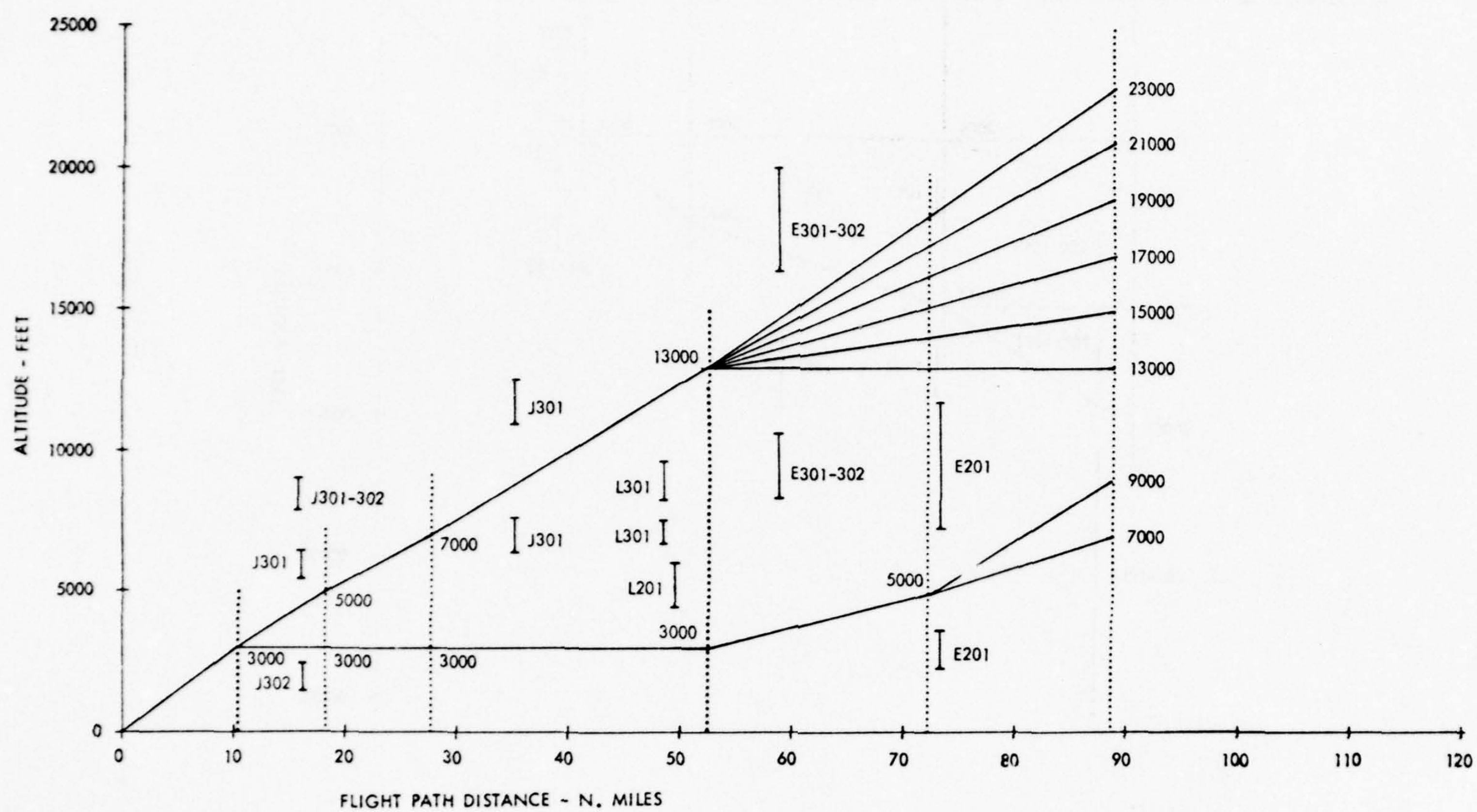


Figure B.3 Kennedy Arrival Route J203

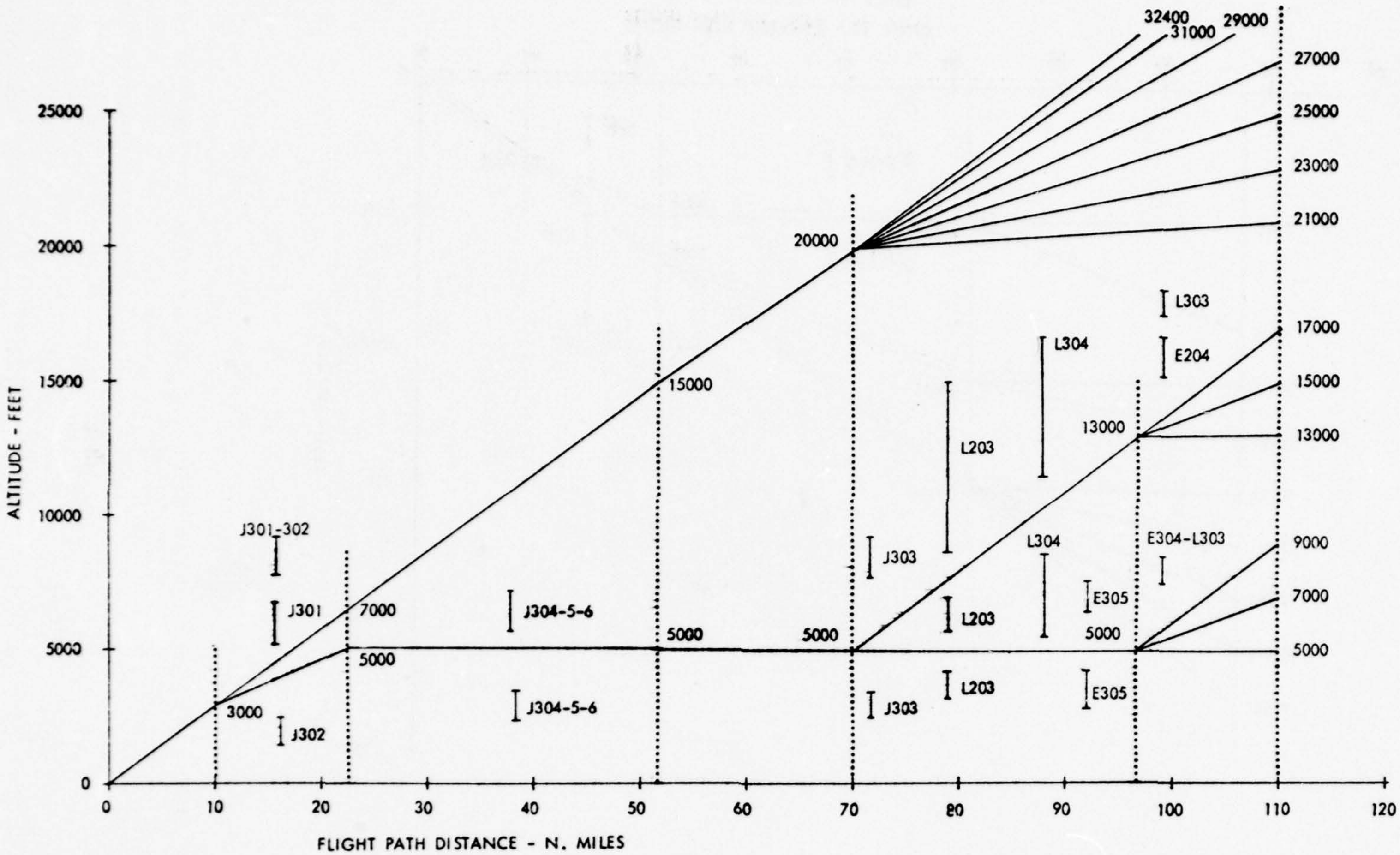


Figure B.4 Kennedy Arrival Route J204

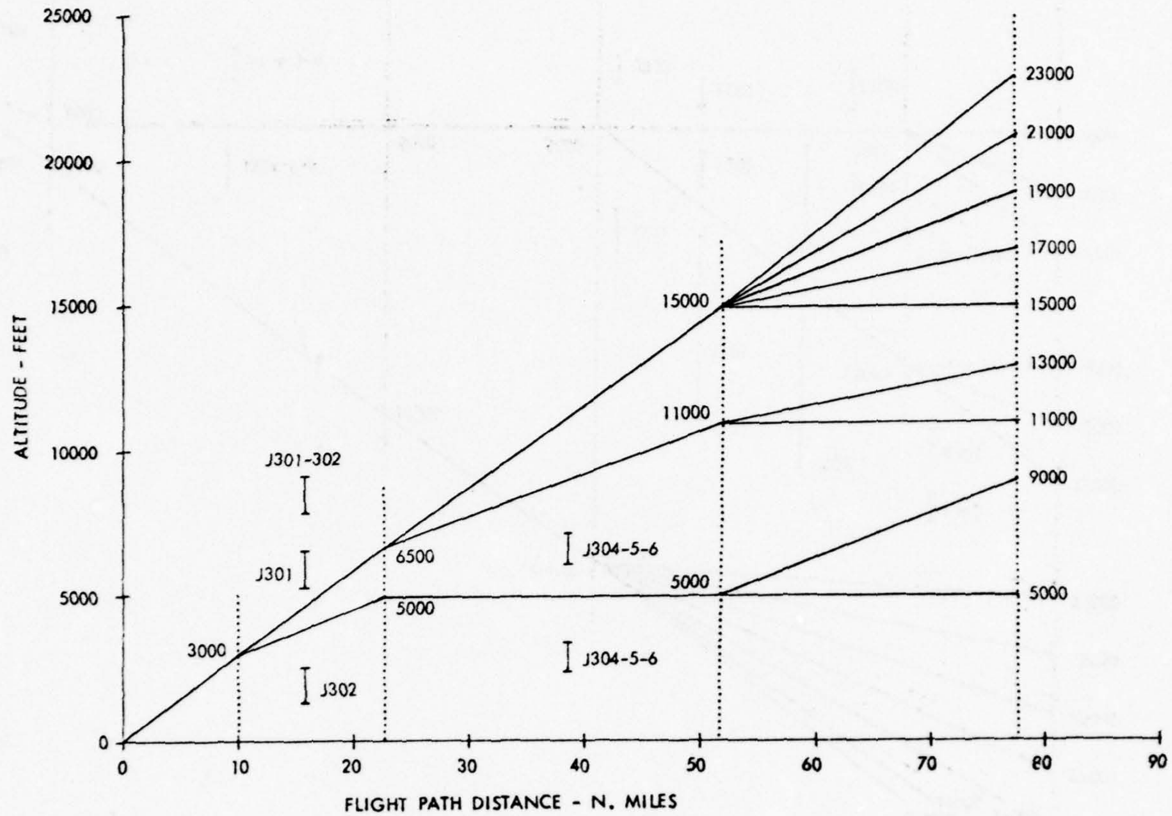


Figure B.5 Kennedy Arrival Route J205

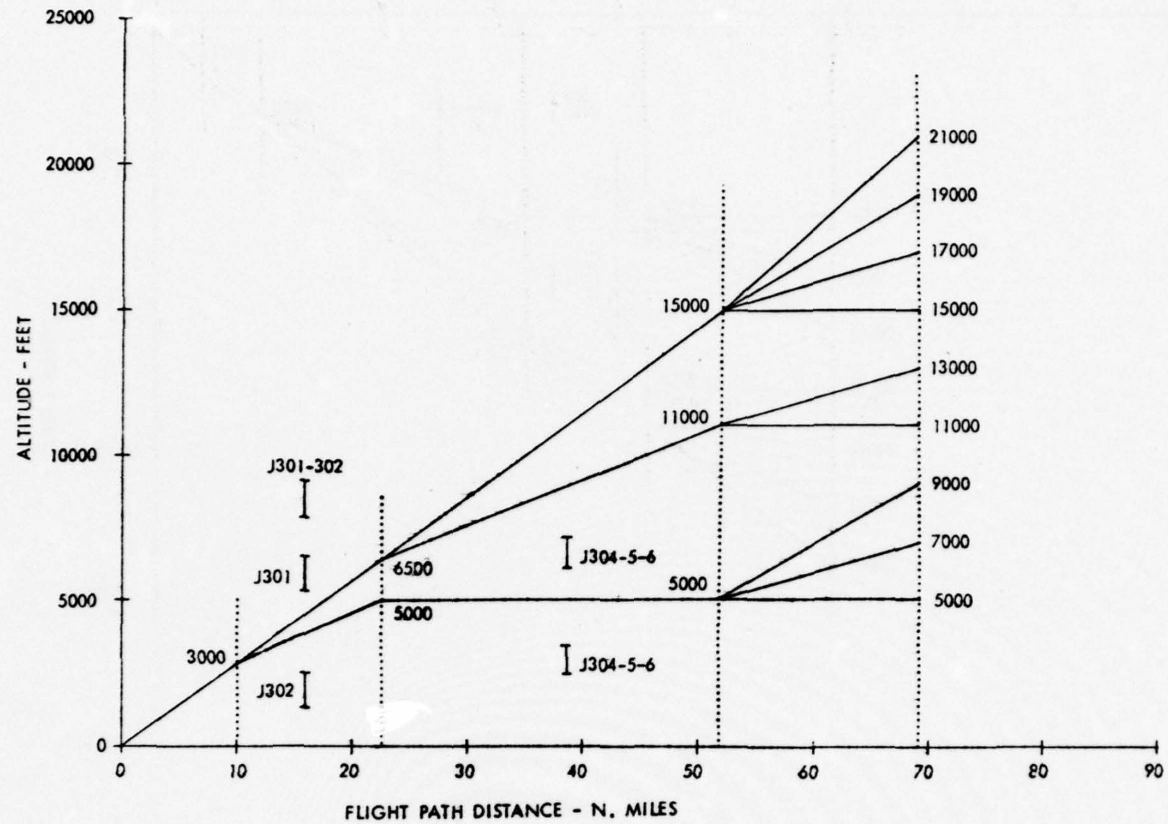


Figure B.6 Kennedy Arrival Route J206

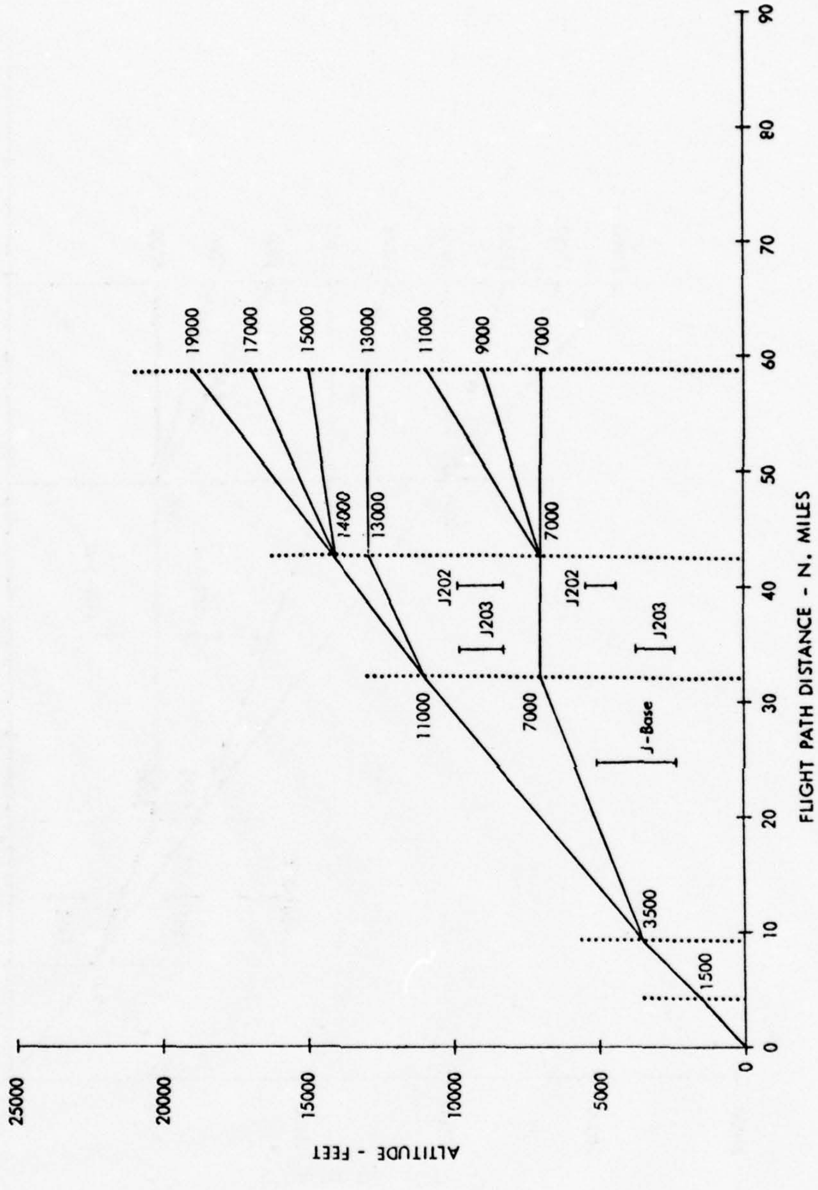


Figure B.7 Kennedy Departure Route J301

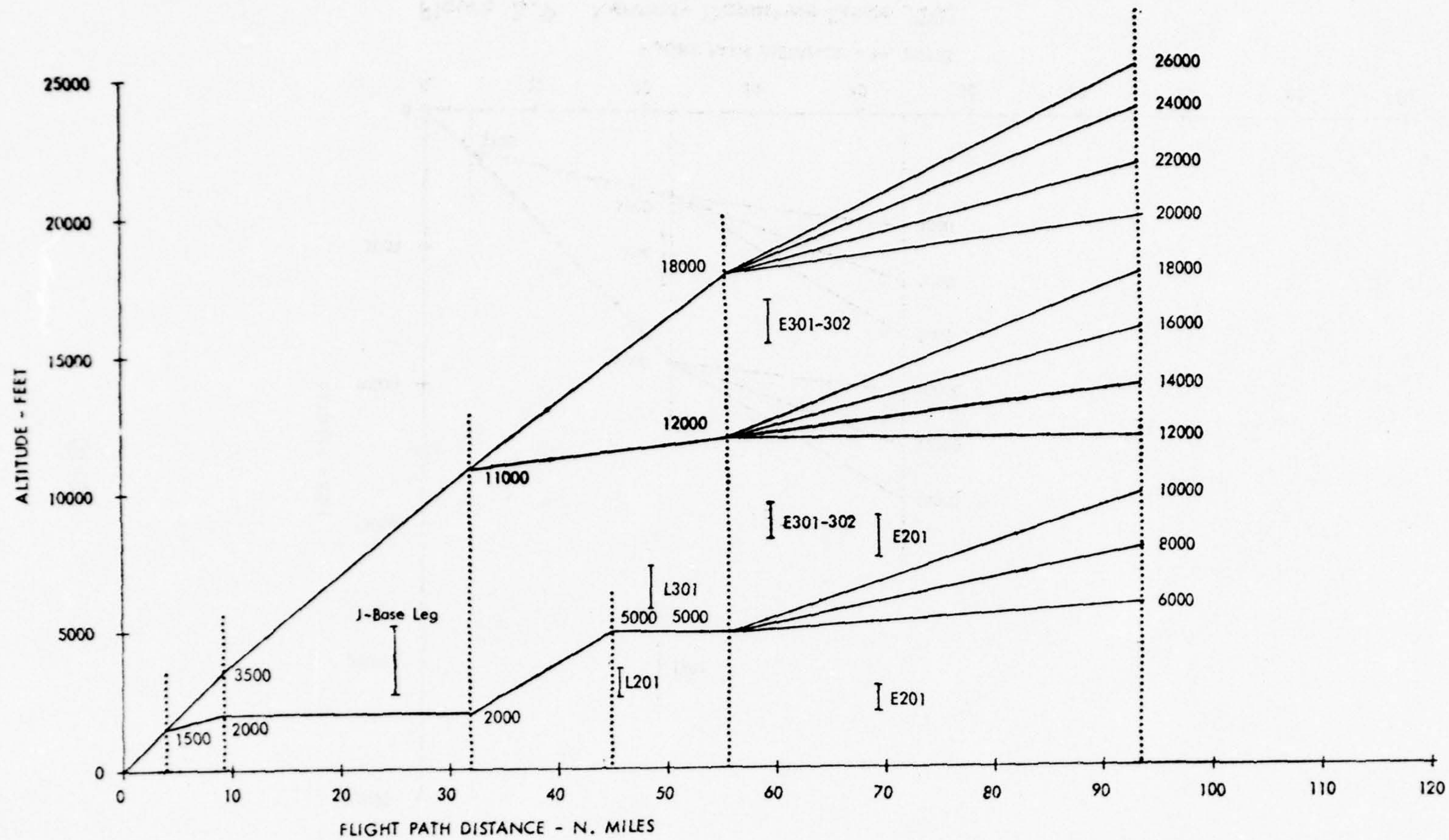


Figure B.8 Kennedy Departure Route J302

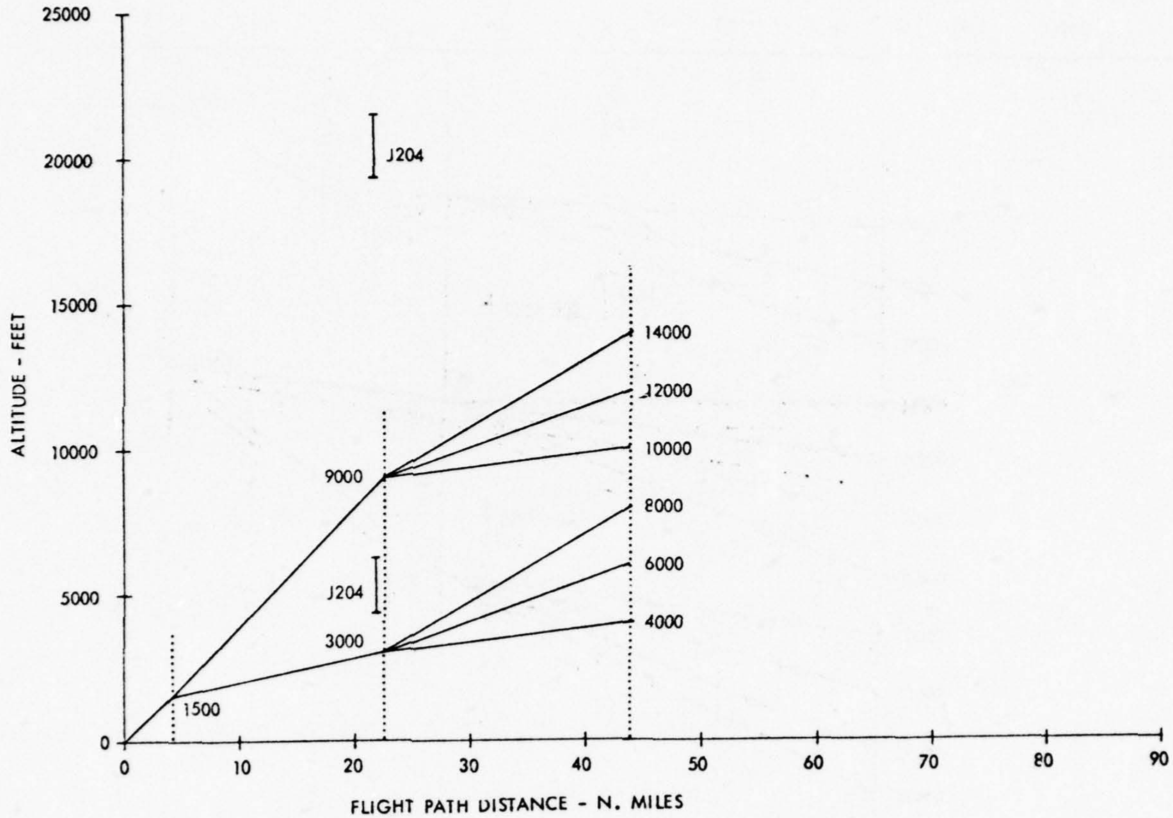


Figure B.9 Kennedy Departure Route J303

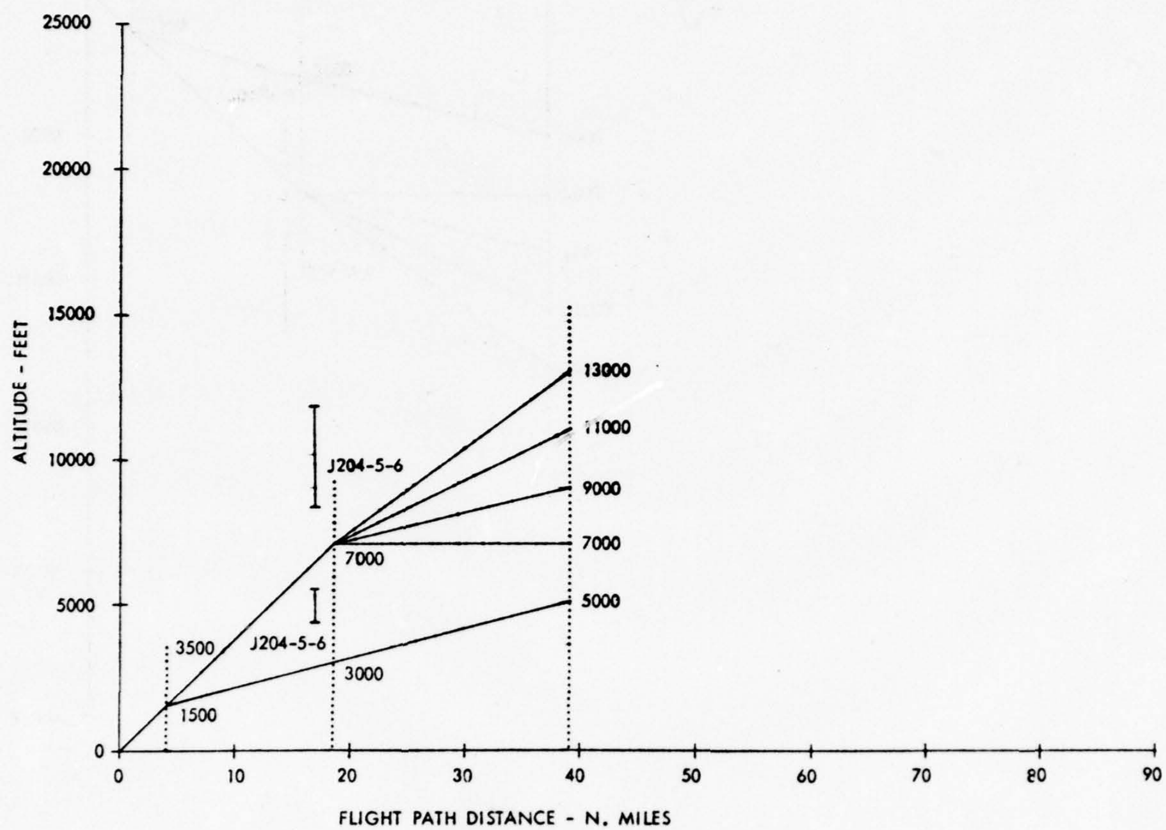


Figure B.10 Kennedy Departure Route J304

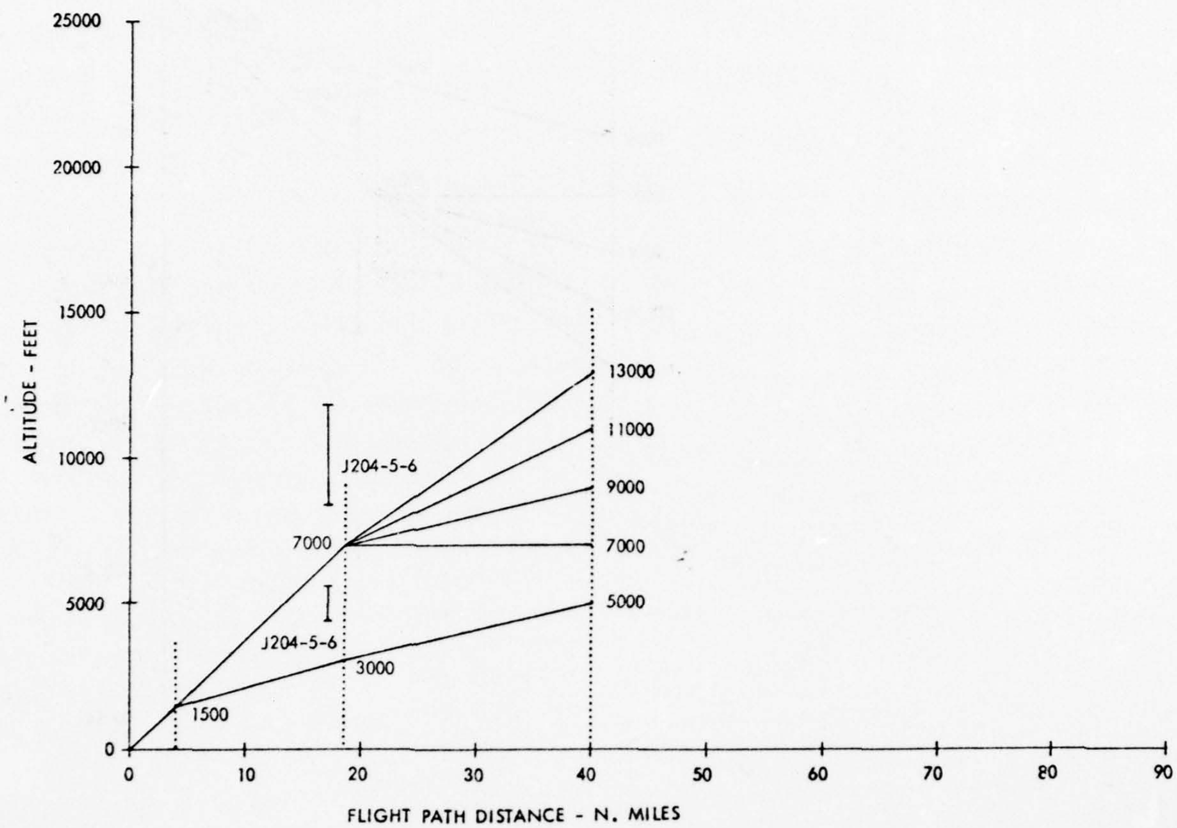


Figure B.11 Kennedy Departure Route J305

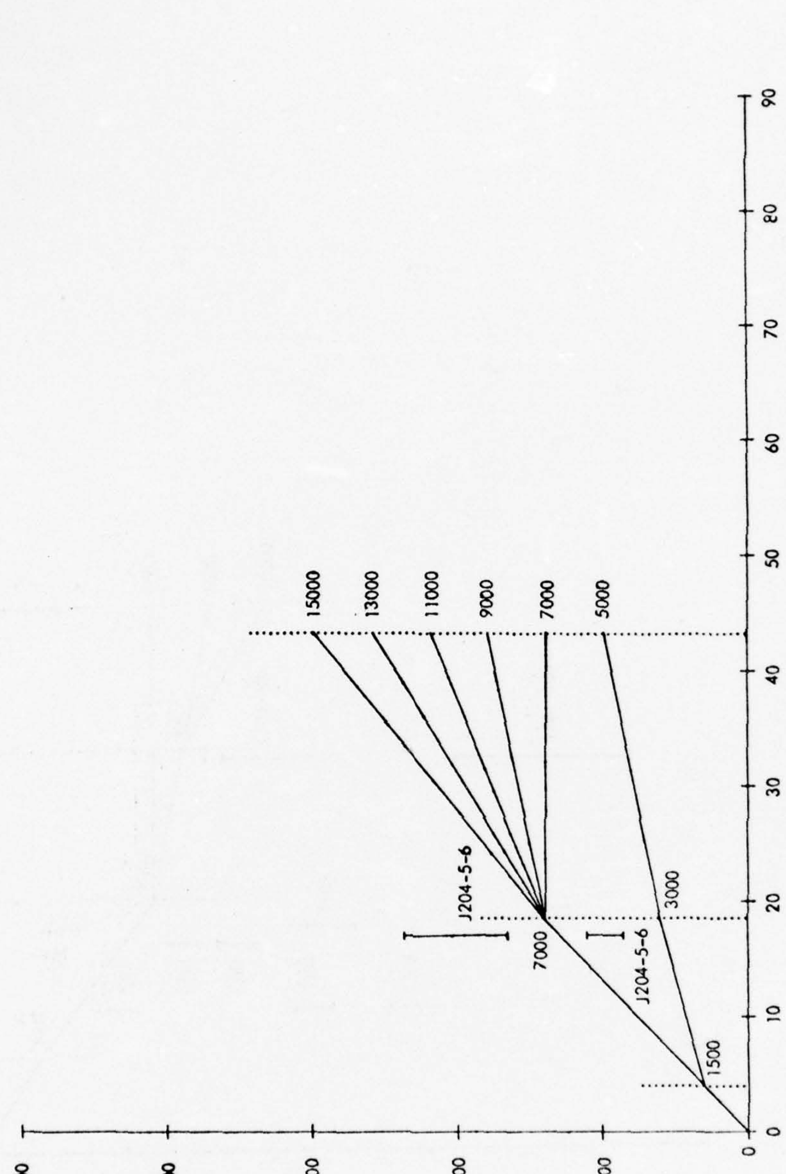


Figure B.12 Kennedy Departure Route J306

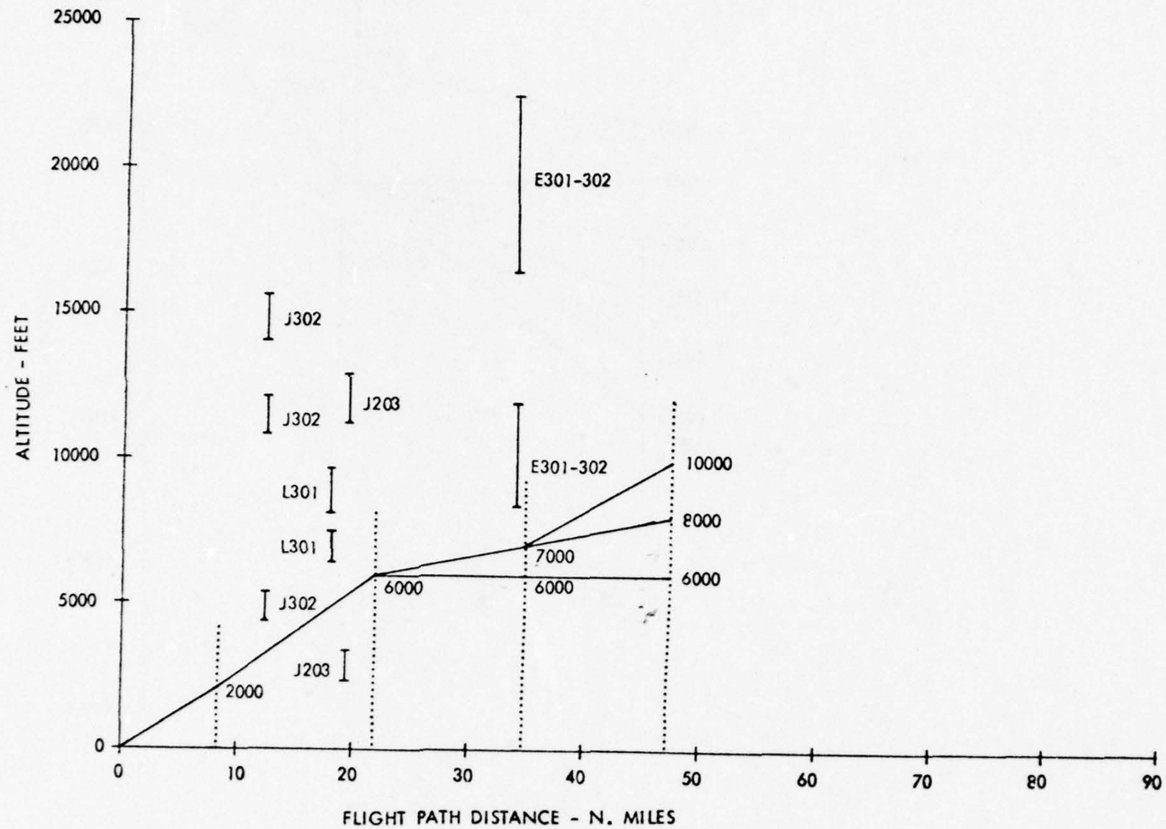


Figure B.13 LaGuardia Arrival Route L201

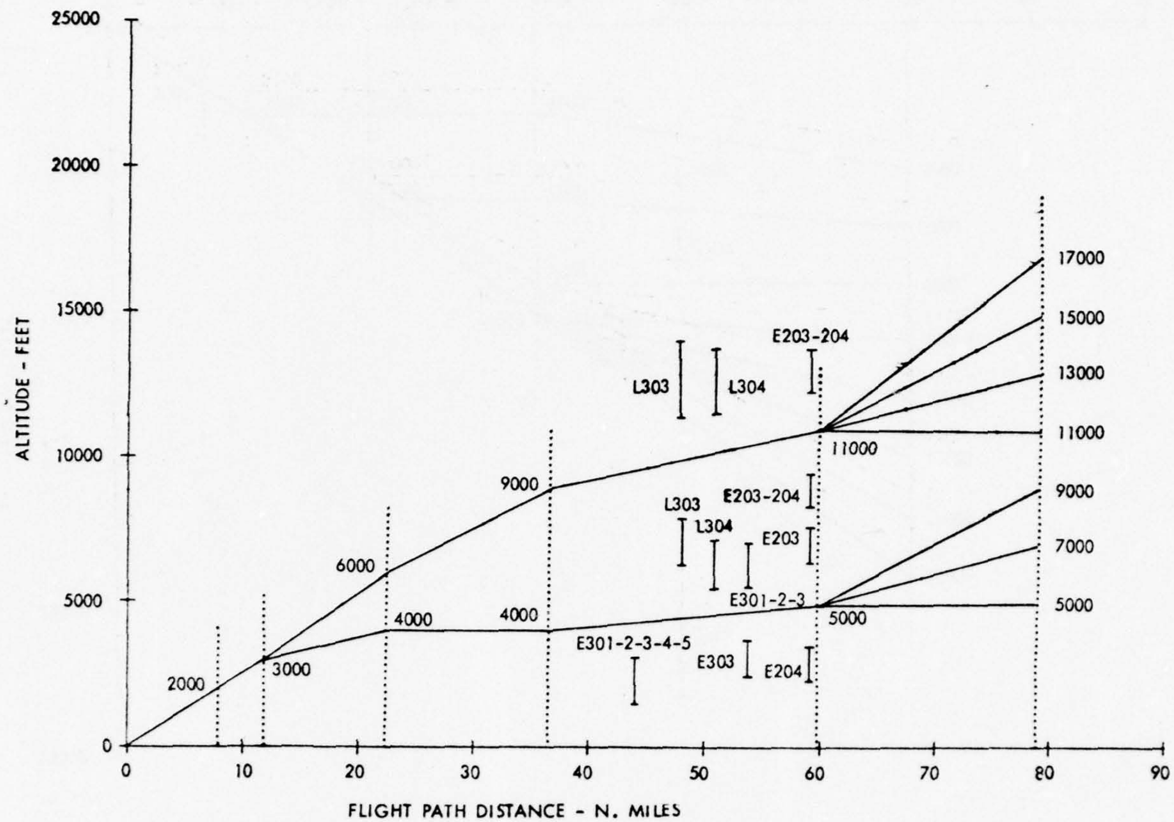


Figure B.14 LaGuardia Arrival Route L202

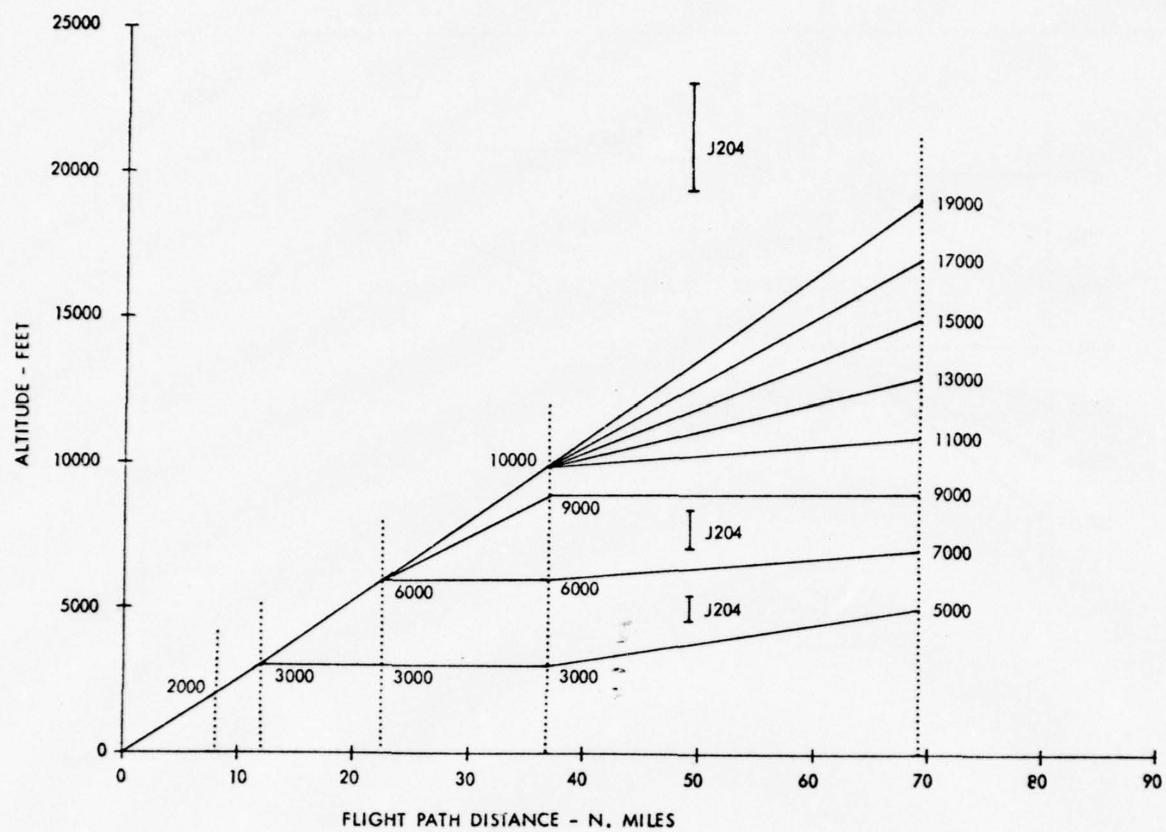


Figure B.15 LaGuardia Arrival Route L203

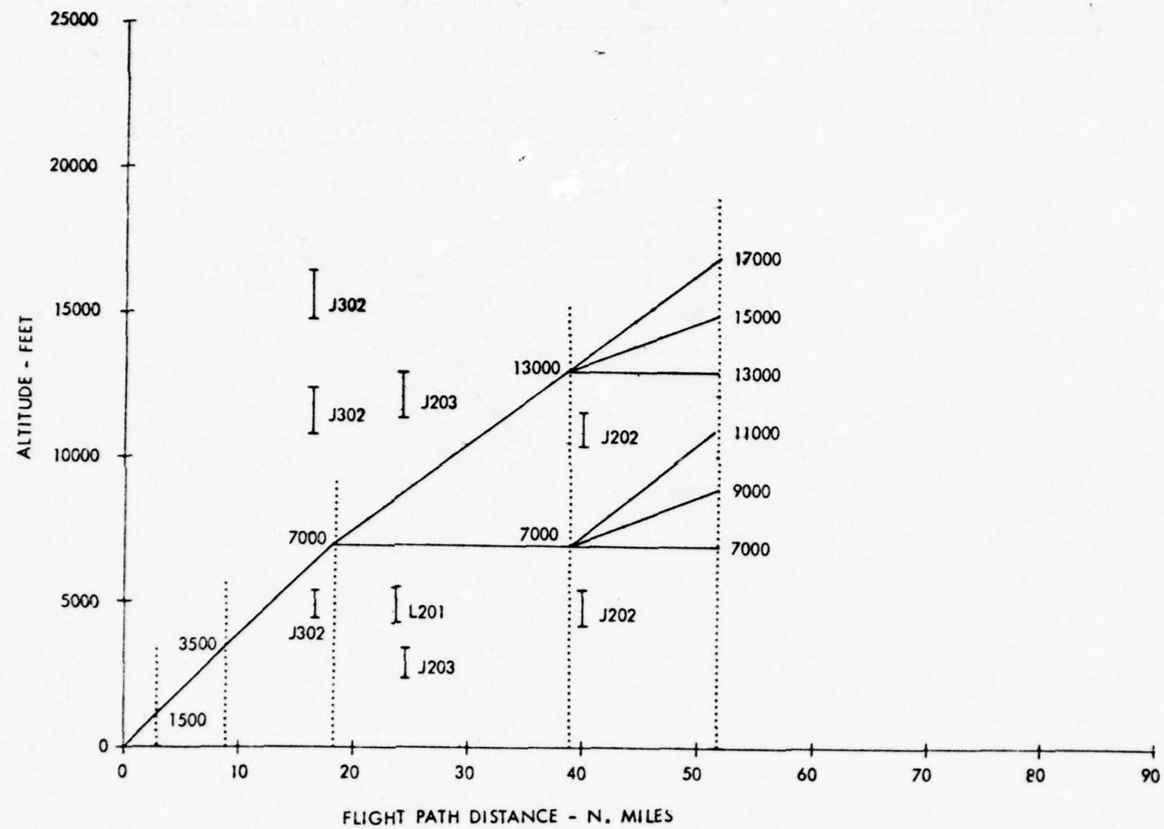


Figure B.16 LaGuardia Departure Route L301

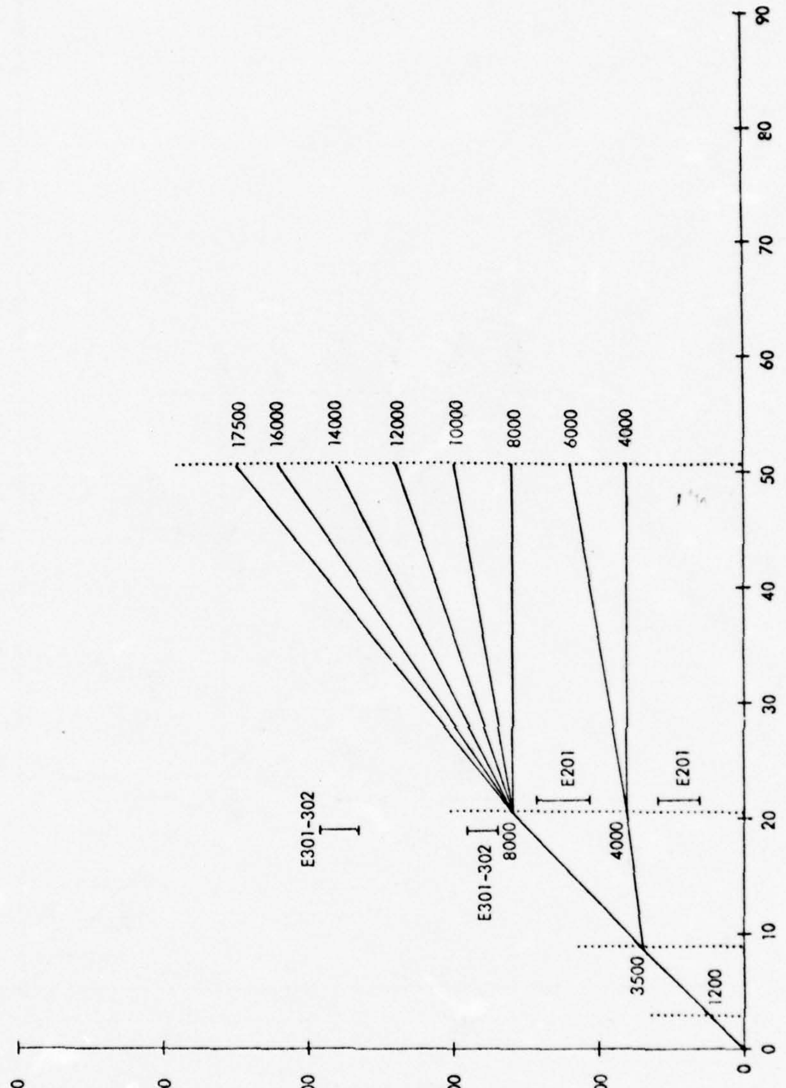


Figure B.17 LaGuardia Departure Route L302

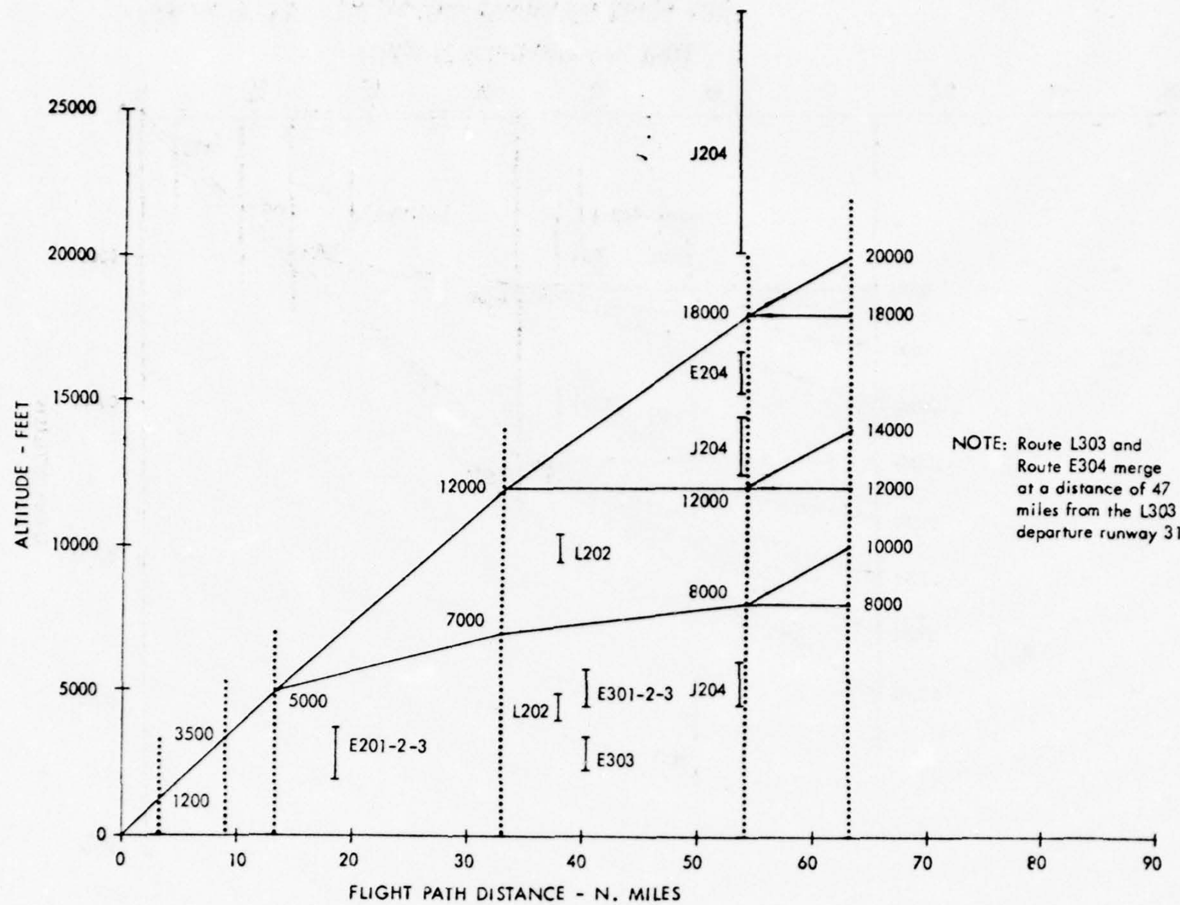


Figure B.18 LaGuardia Departure Route L303

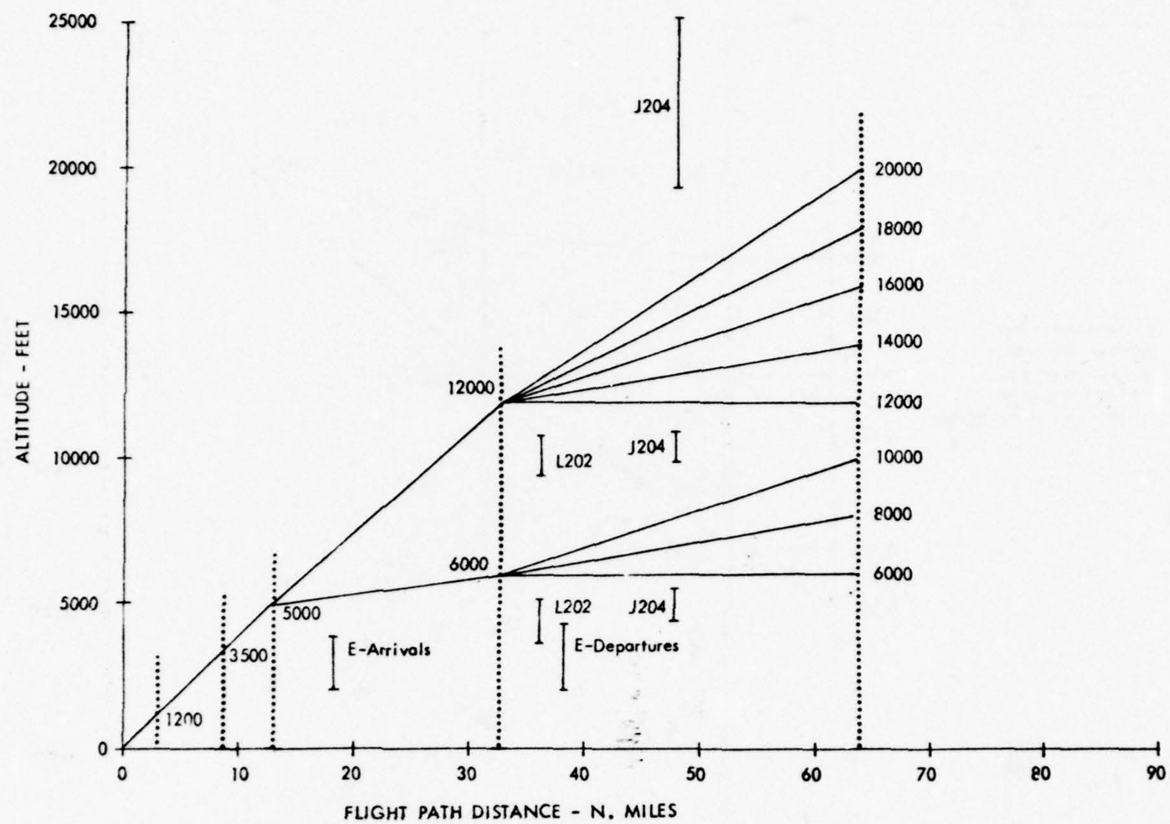


Figure B.19 LaGuardia Departure Route L304

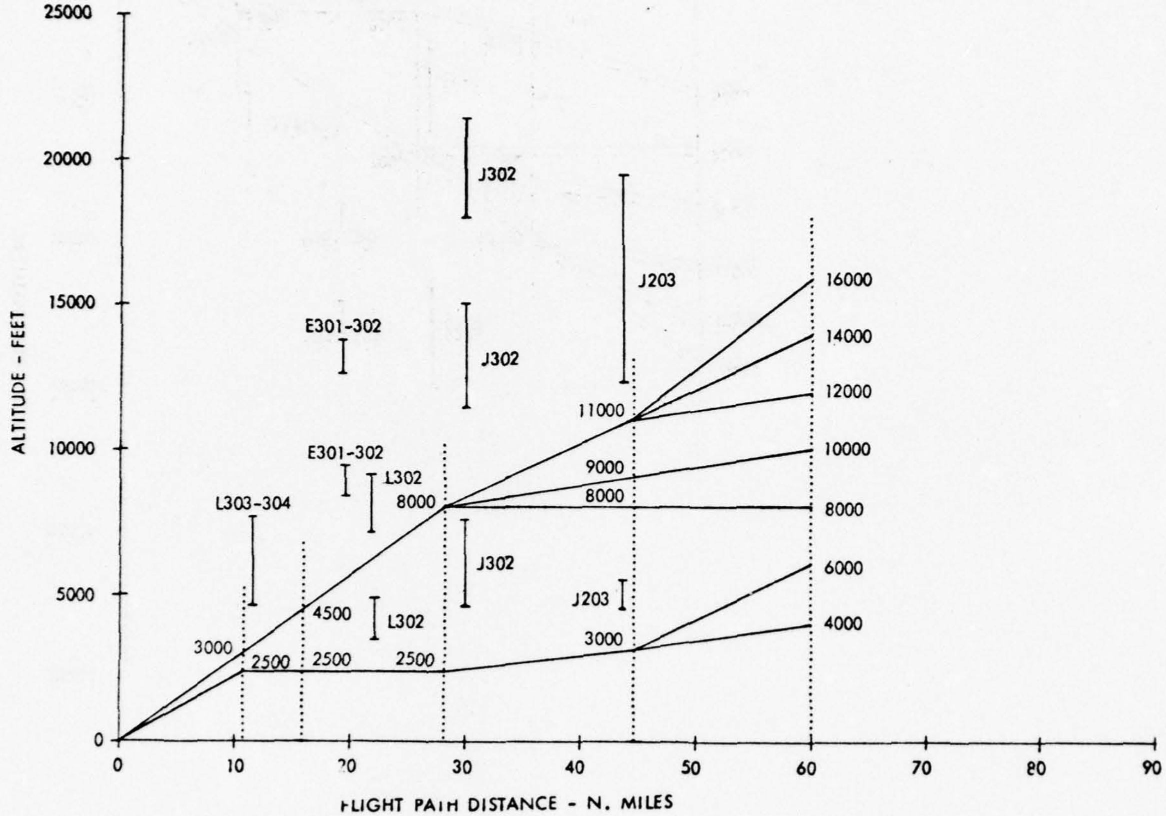


Figure B.20 Newark Arrival Route E201

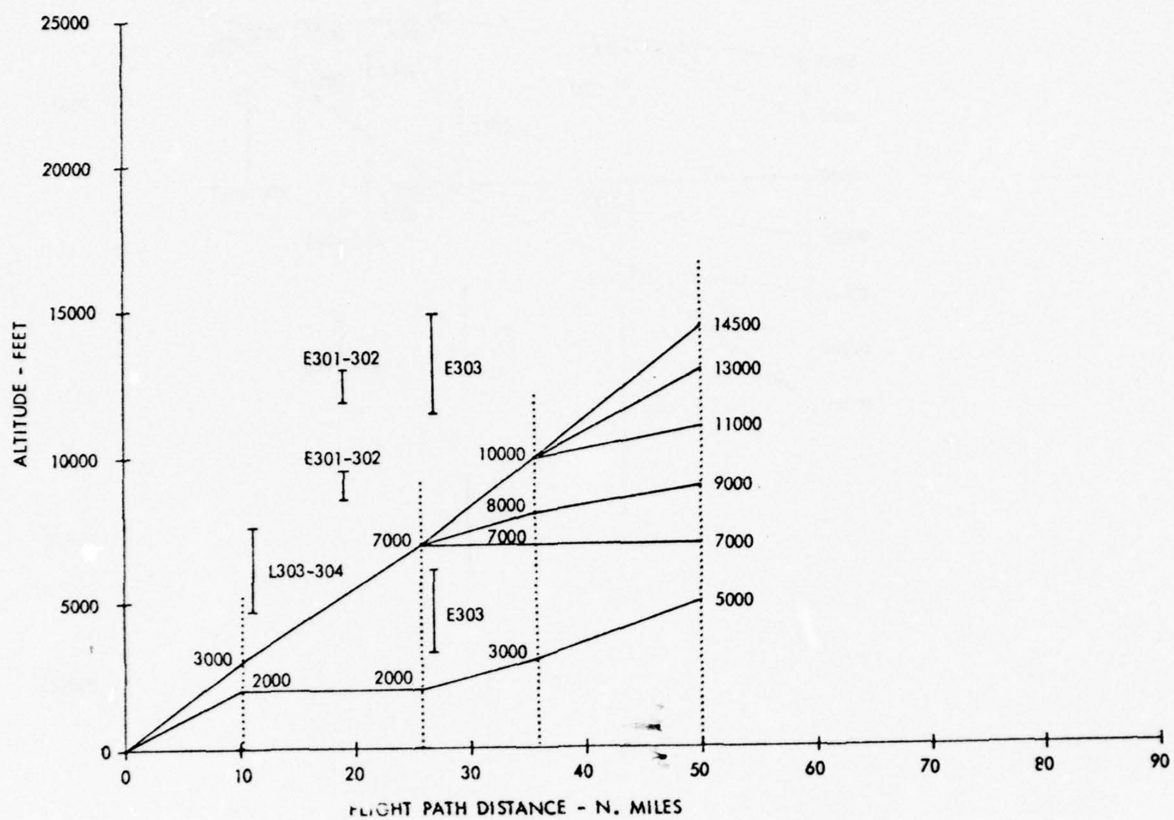


Figure B.21 Newark Arrival Route E202

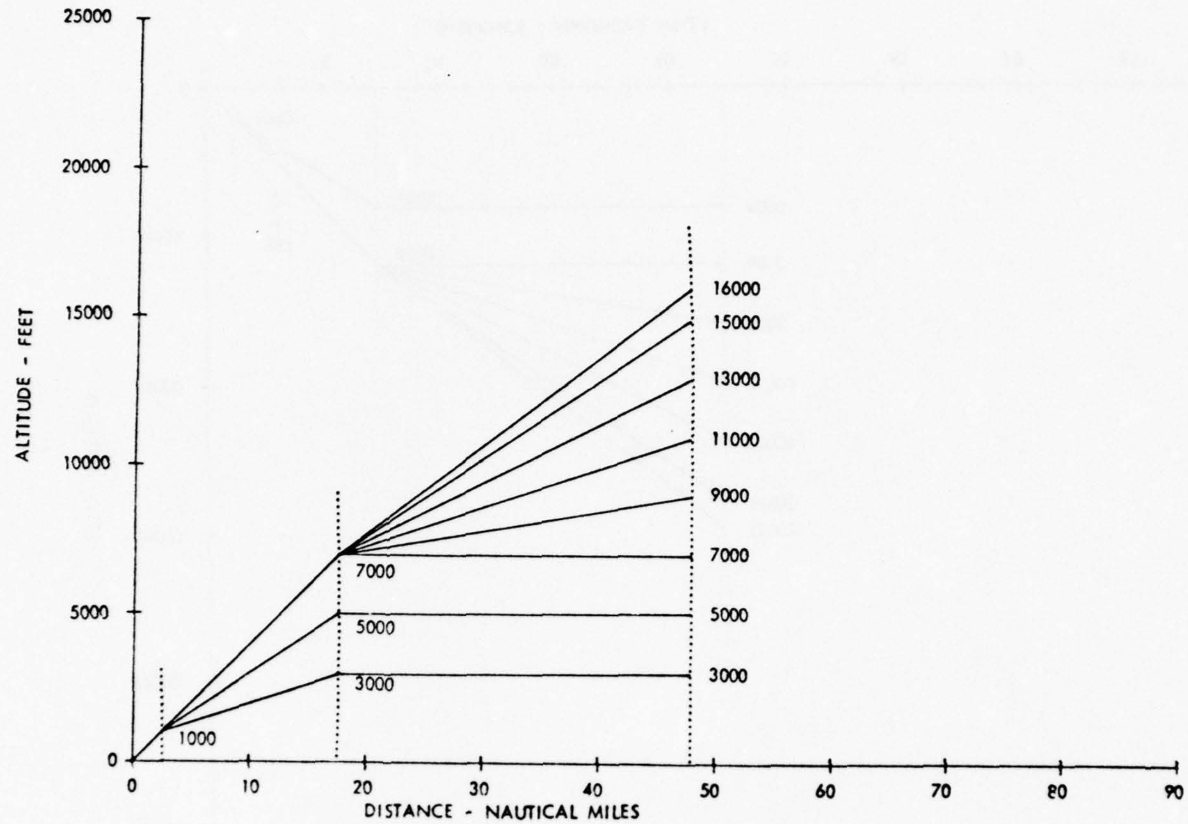


Figure C.13 Departure Route 306, East Flow

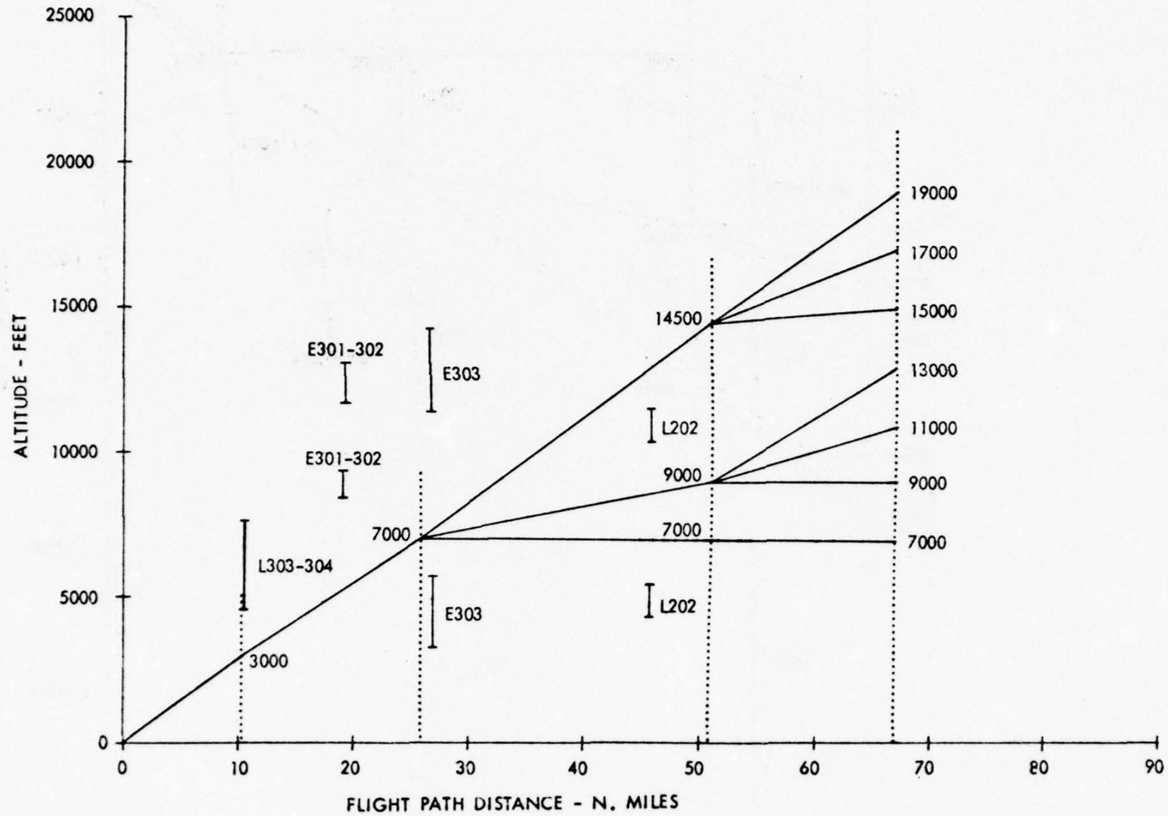


Figure B.22 Newark Arrival Route E203

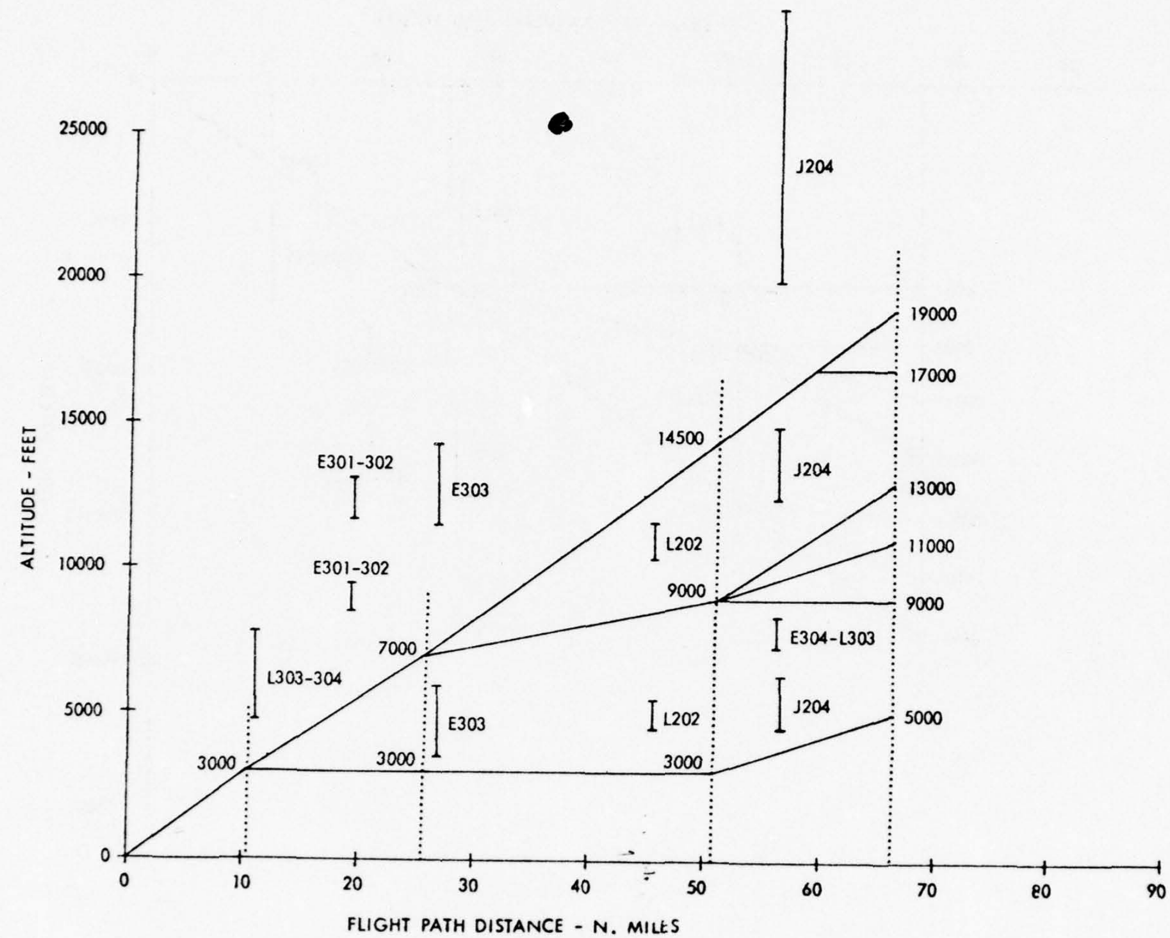


Figure B.23 Newark Arrival Route E204

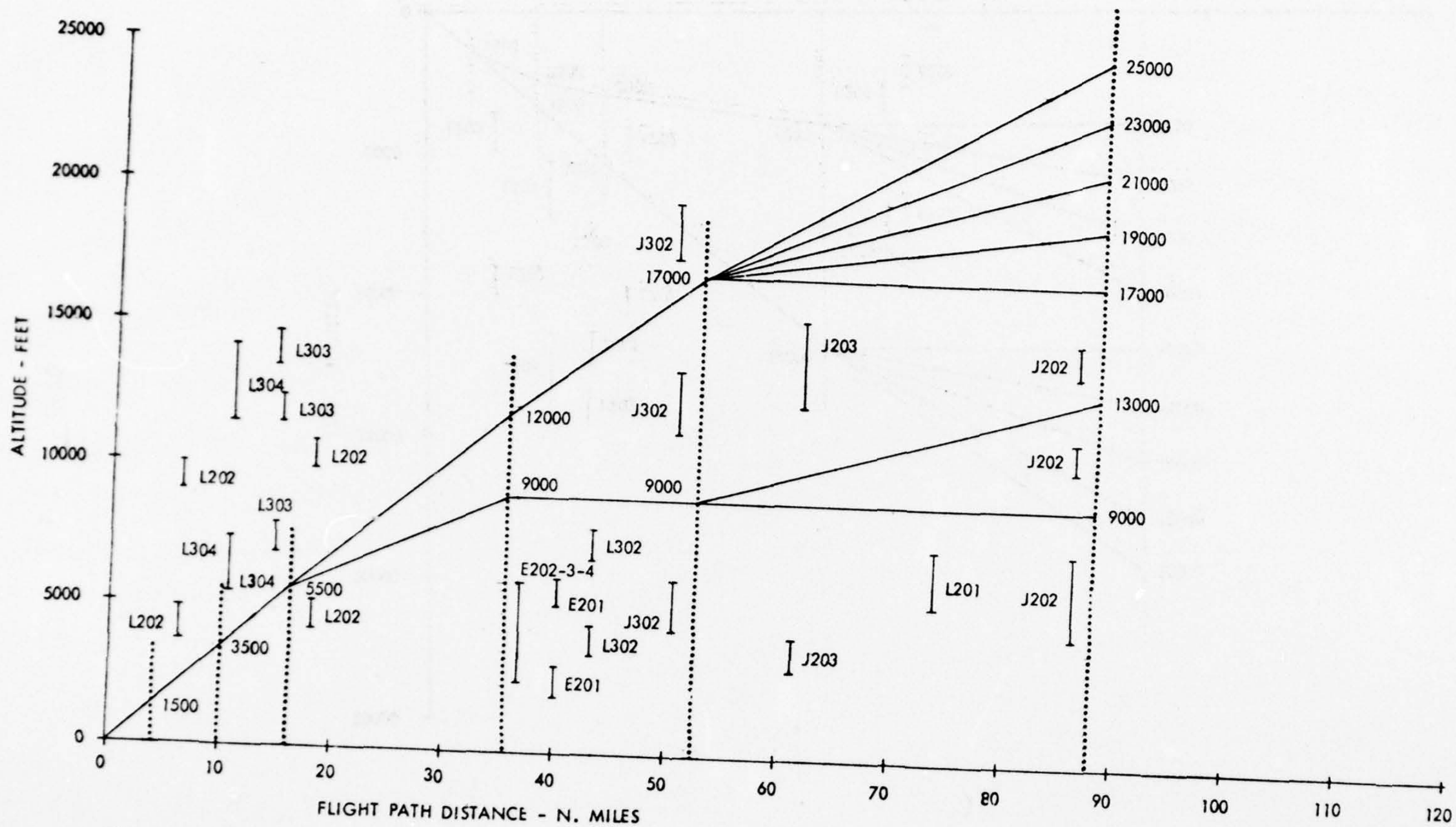


Figure B.24 Newark Departure Route E301-302

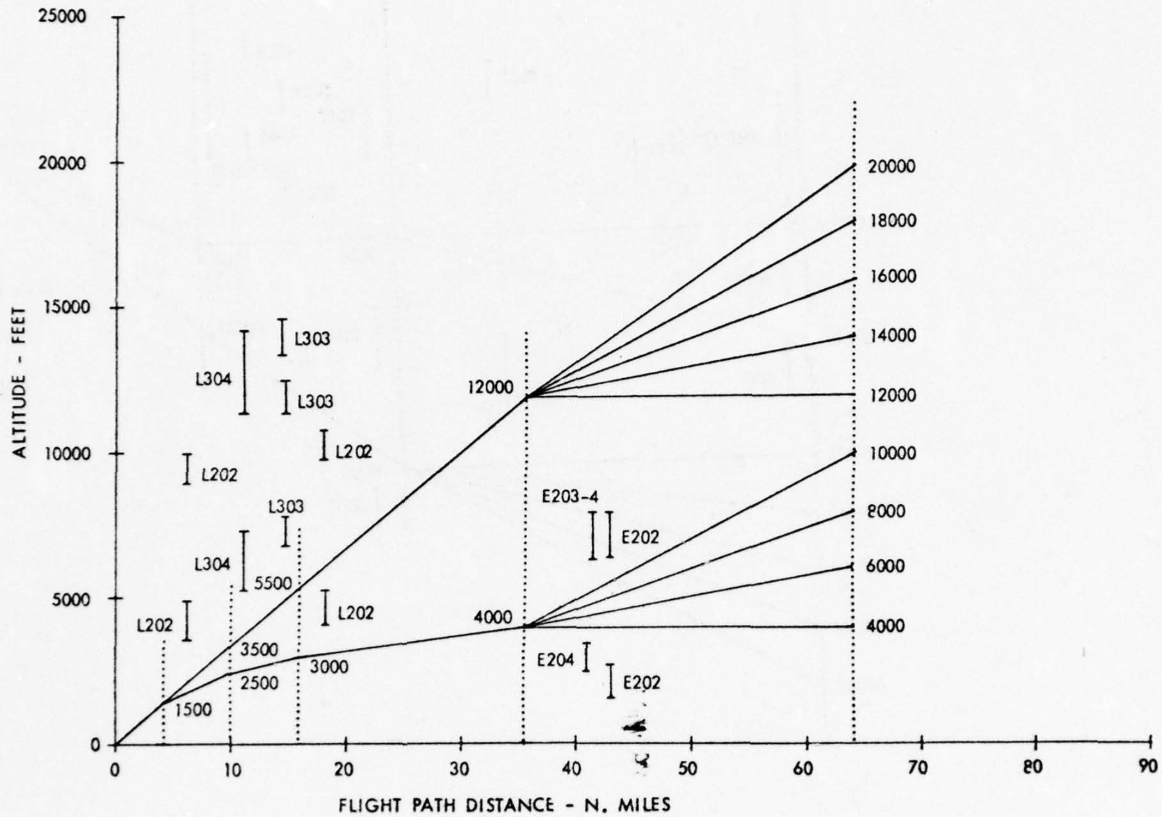


Figure B.25 Newark Departure Route E303

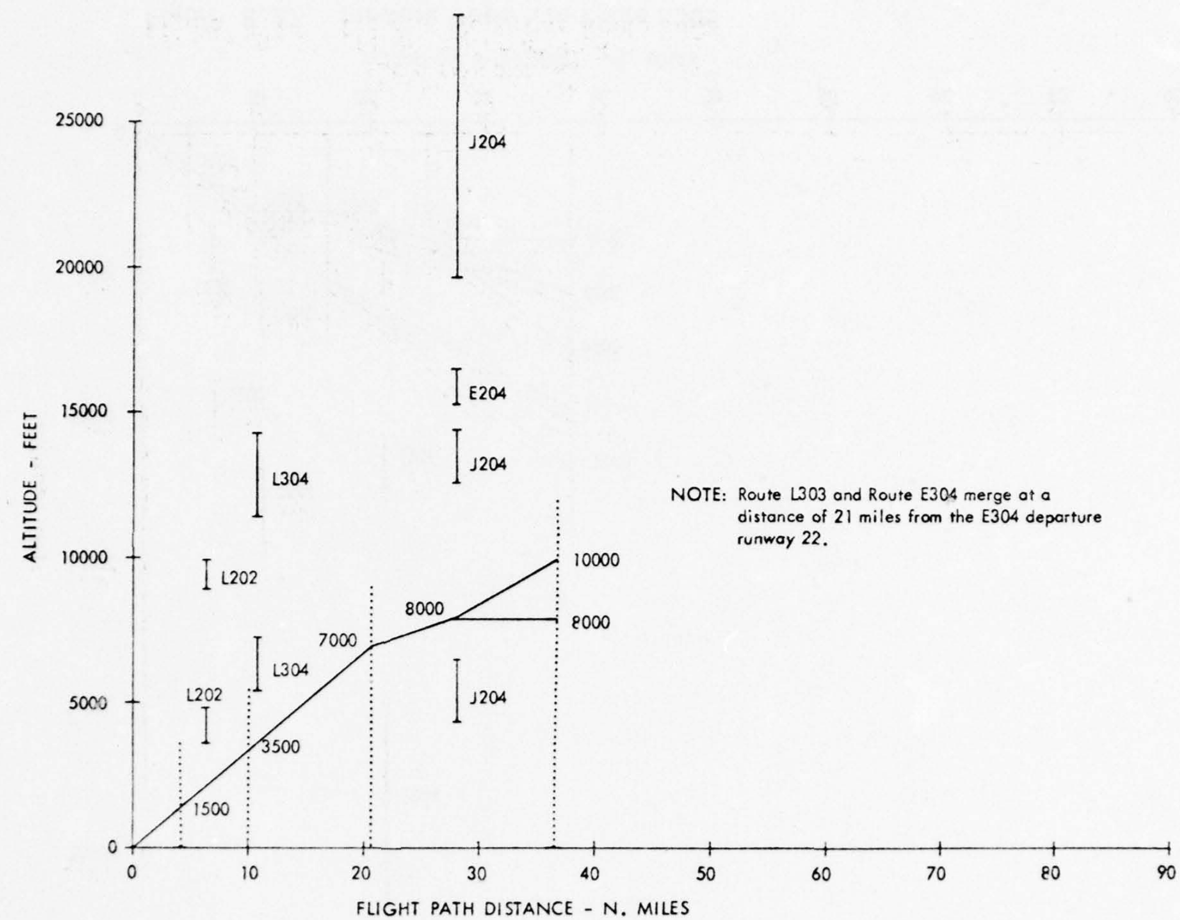


Figure B.26 Newark Departure Route E304

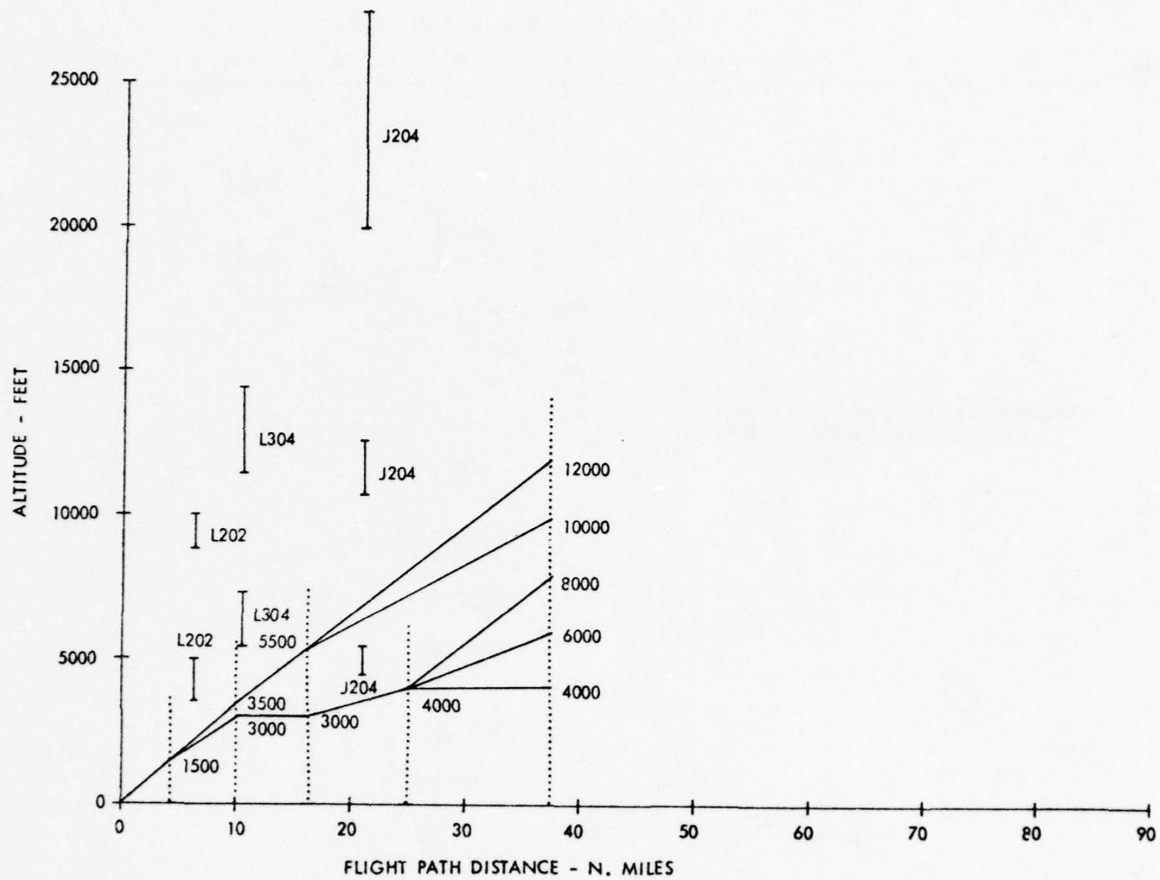


Figure B.27 Newark Departure Route E305

APPENDIX C

NEW ORLEANS TERMINAL AREA 3D DESIGN

This appendix contains vertical route profiles for the initial post-1982 New Orleans terminal area. These profiles are based upon the fixed gradient approach to 3D route design. The basic route structure is presented in Section 7.3.2 of this report.

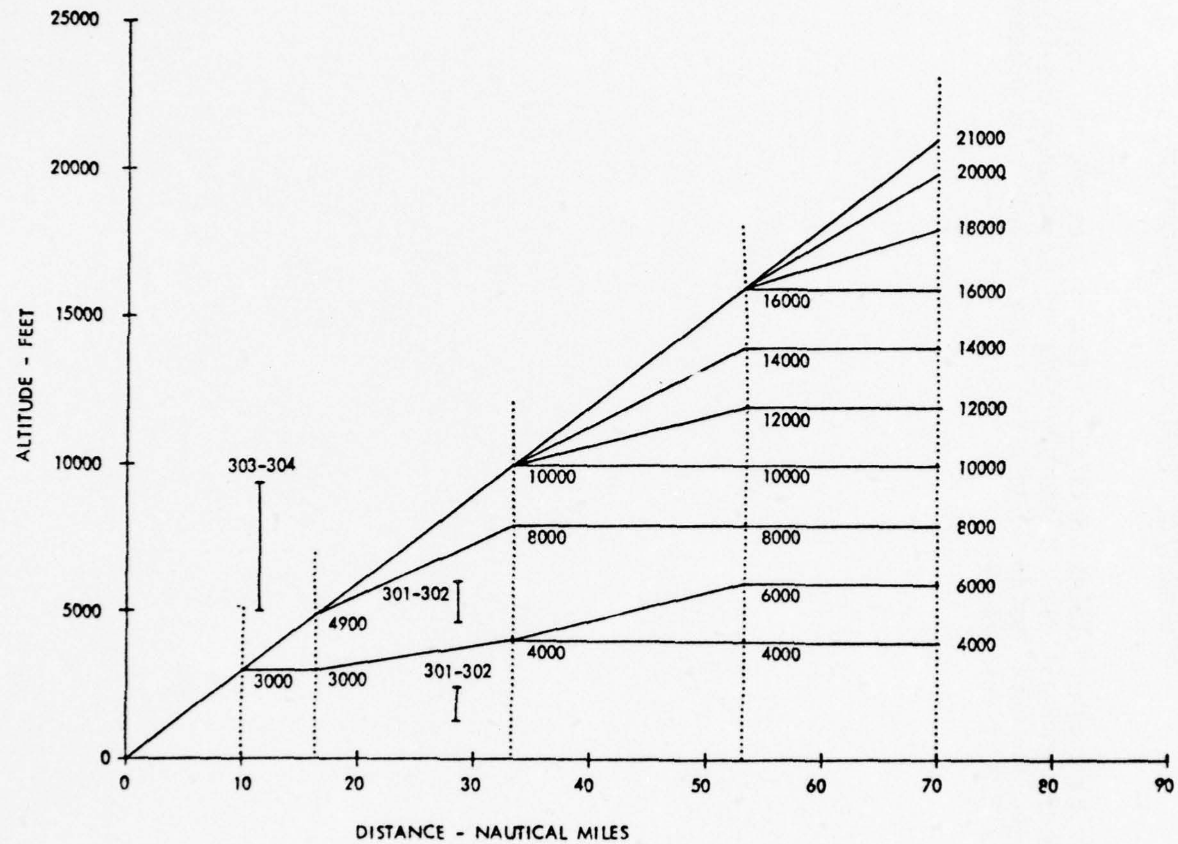


Figure C.1 Arrival Route 201, East Flow

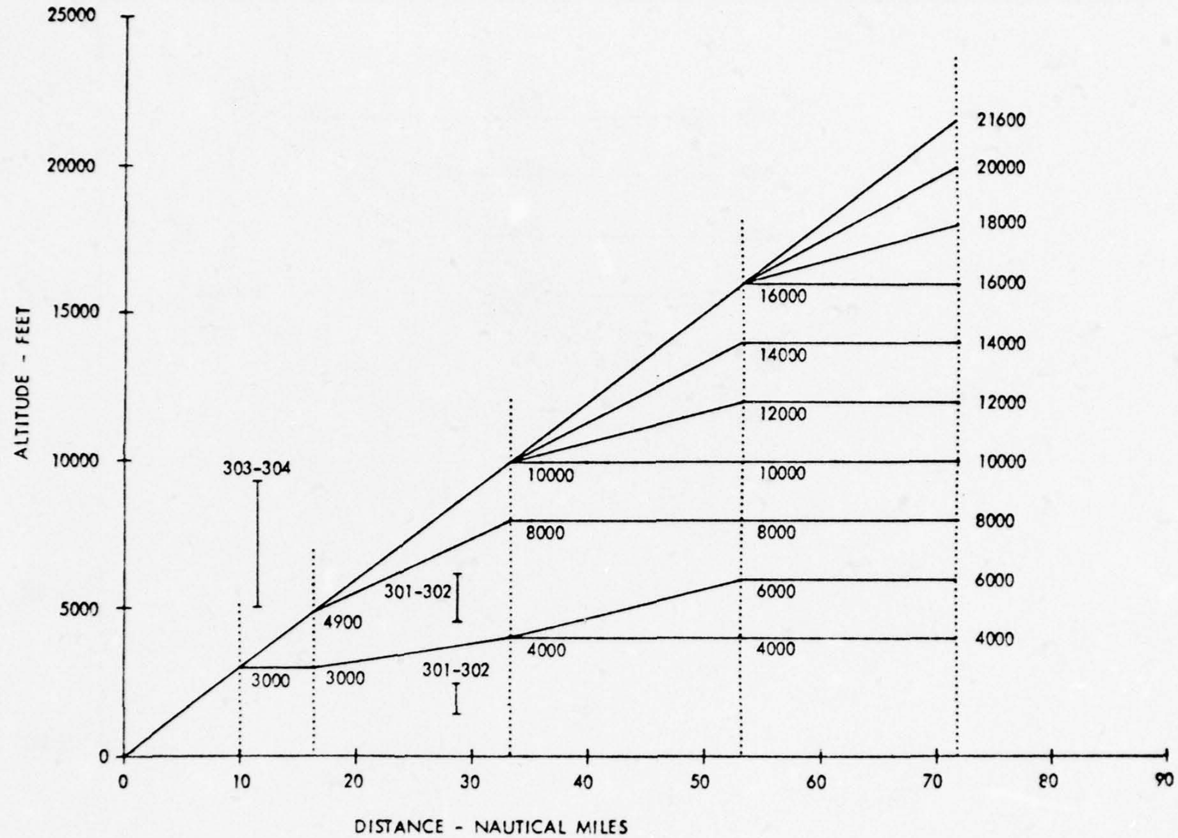


Figure C.2 Arrival Route 202, East Flow

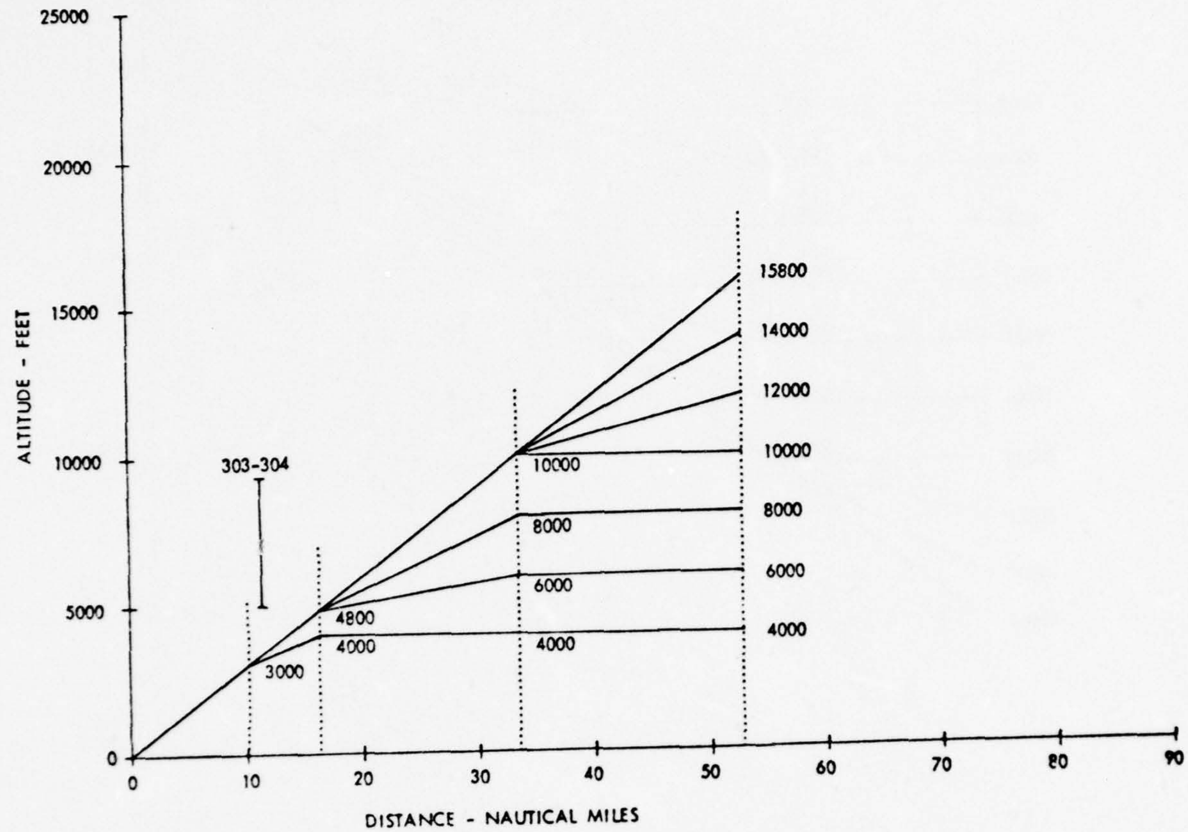


Figure C.3 Arrival Route 203, East Flow

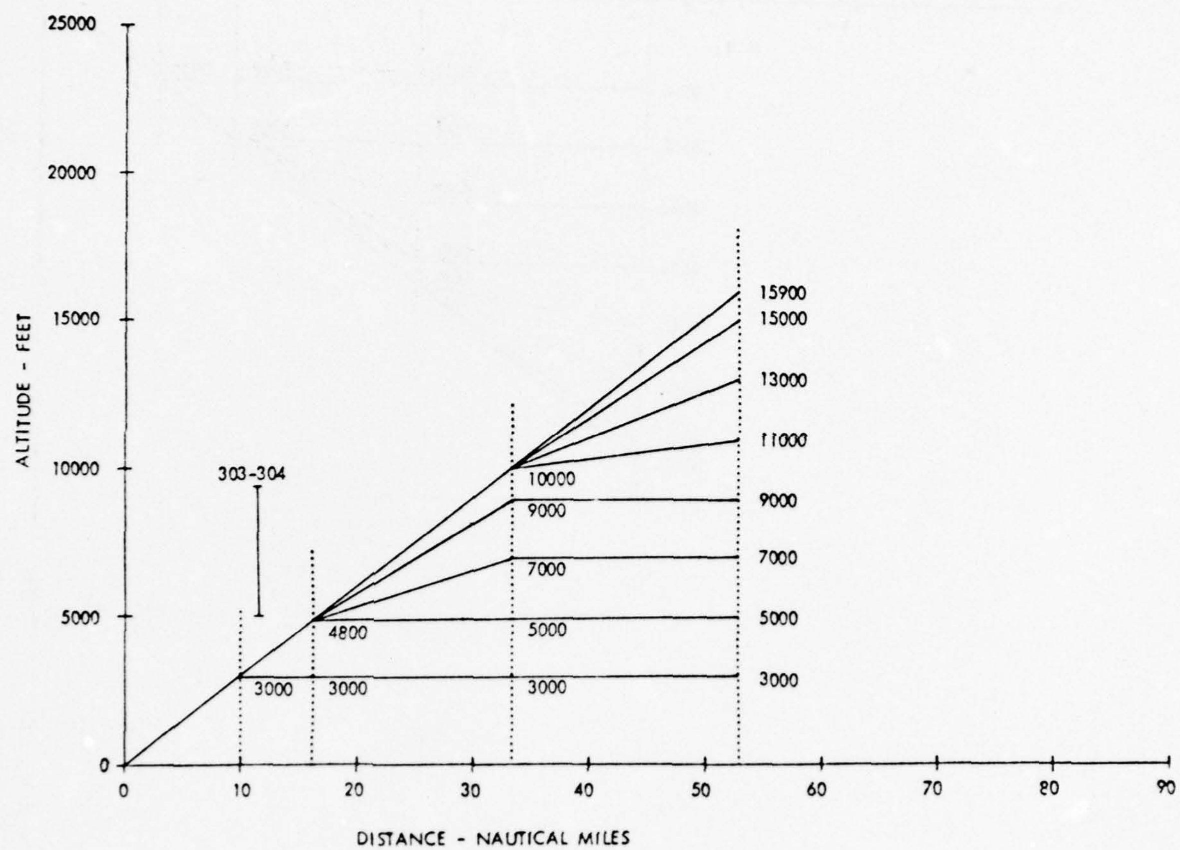


Figure C.4 Arrival Route 204, East Flow

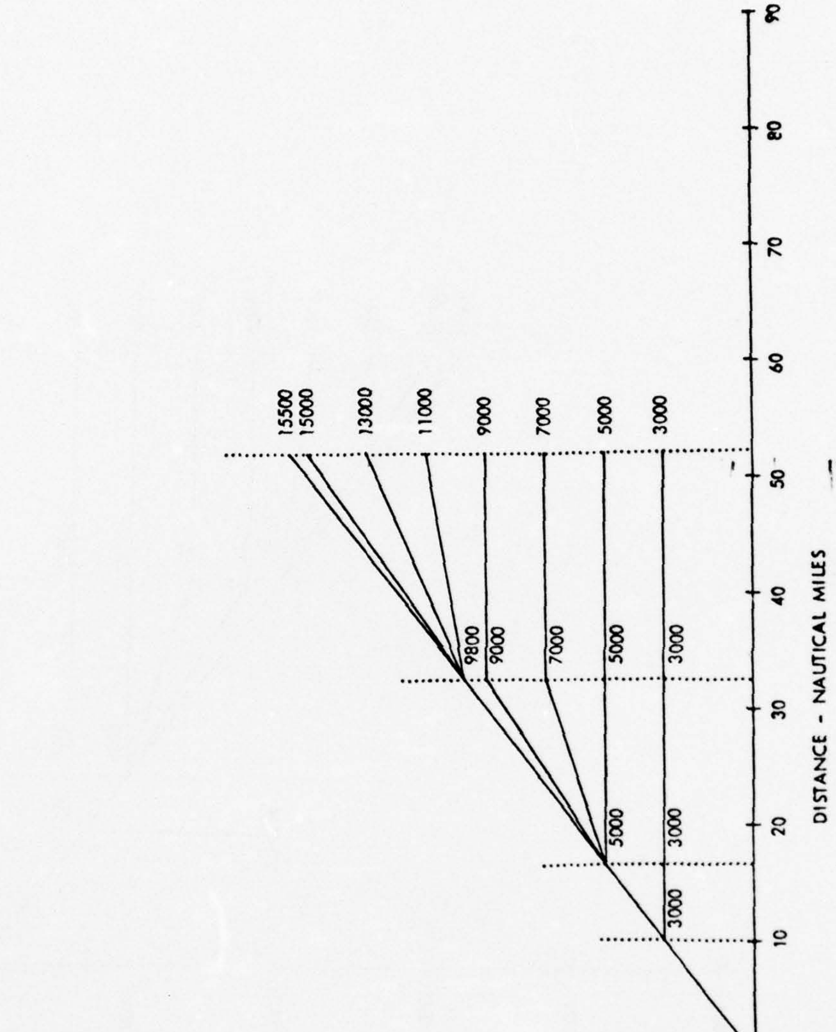


Figure C.5 Arrival Route 205, East Flow

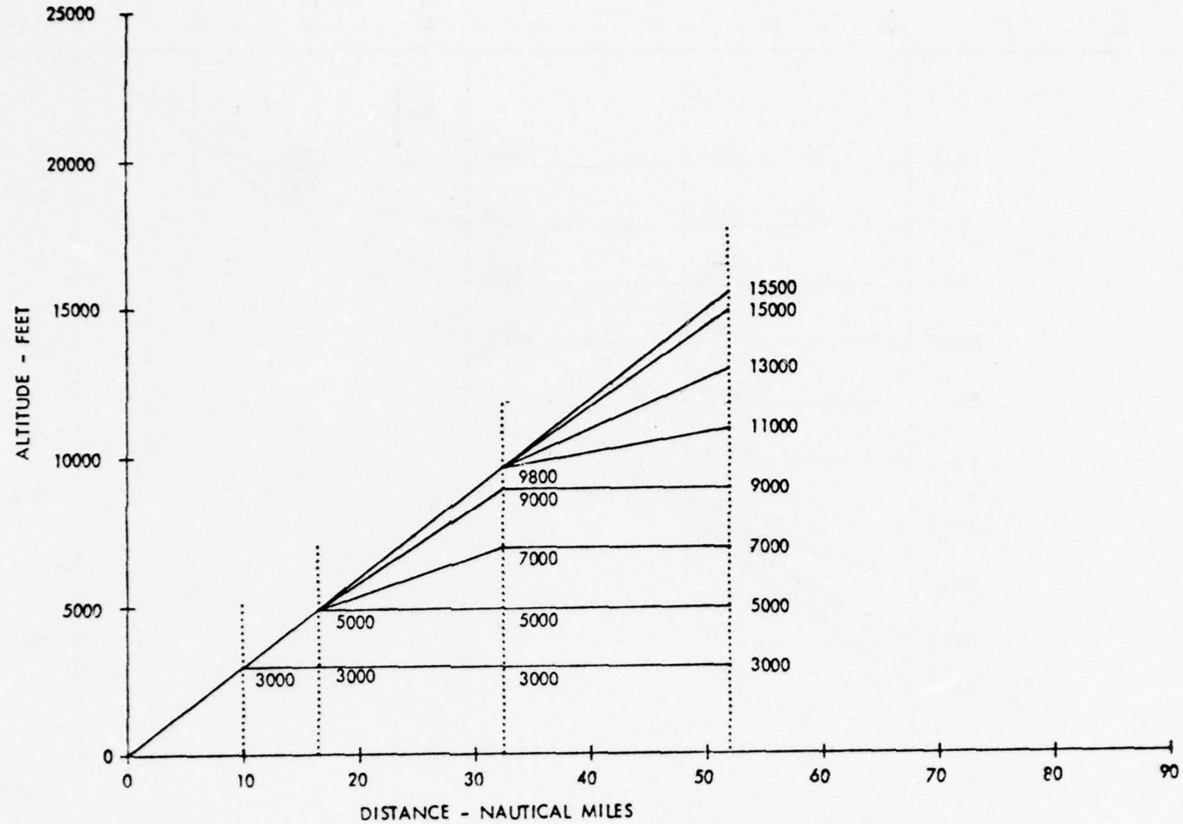


Figure C.6 Arrival Route 206, East Flow

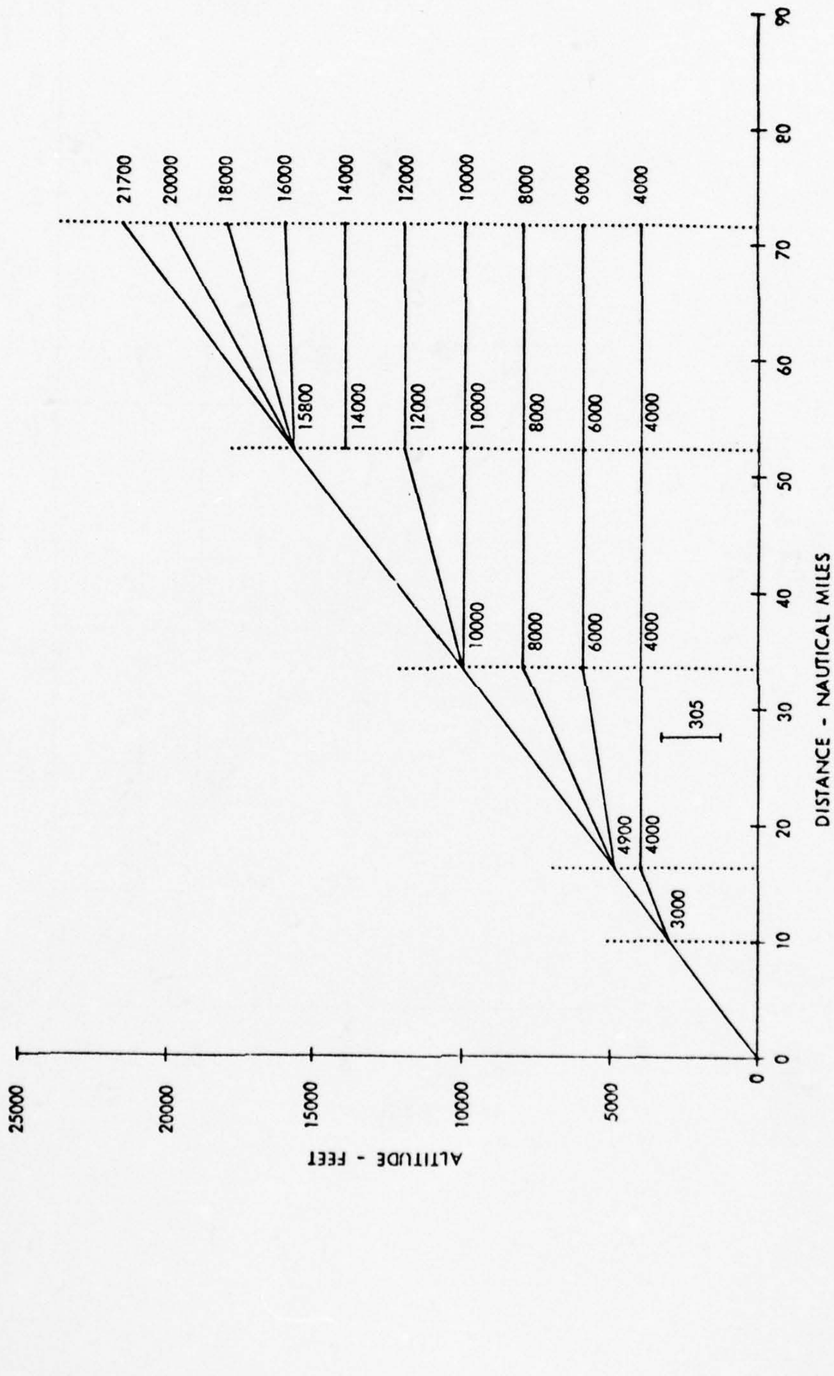


Figure C.7 Arrival Route 207, East Flow

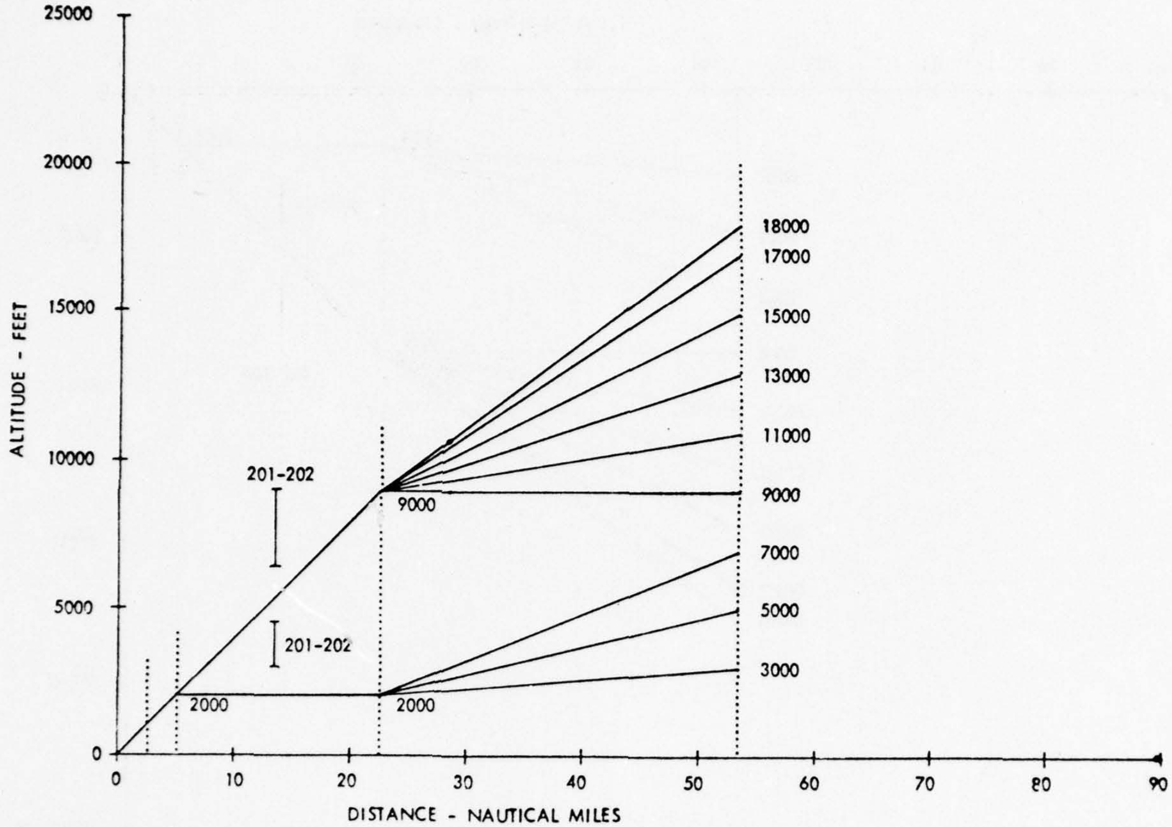


Figure C.8 Arrival Route 301, East Flow

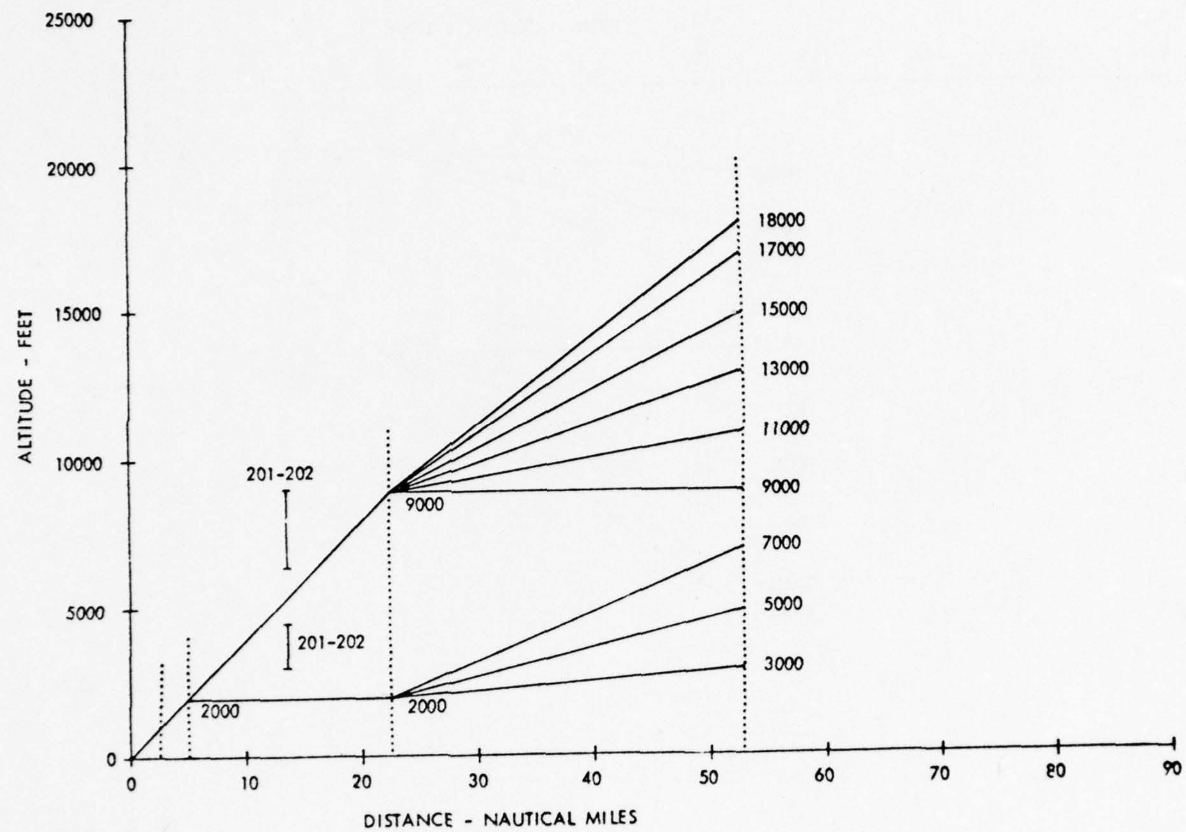


Figure C.9 Departure Route 302, East Flow

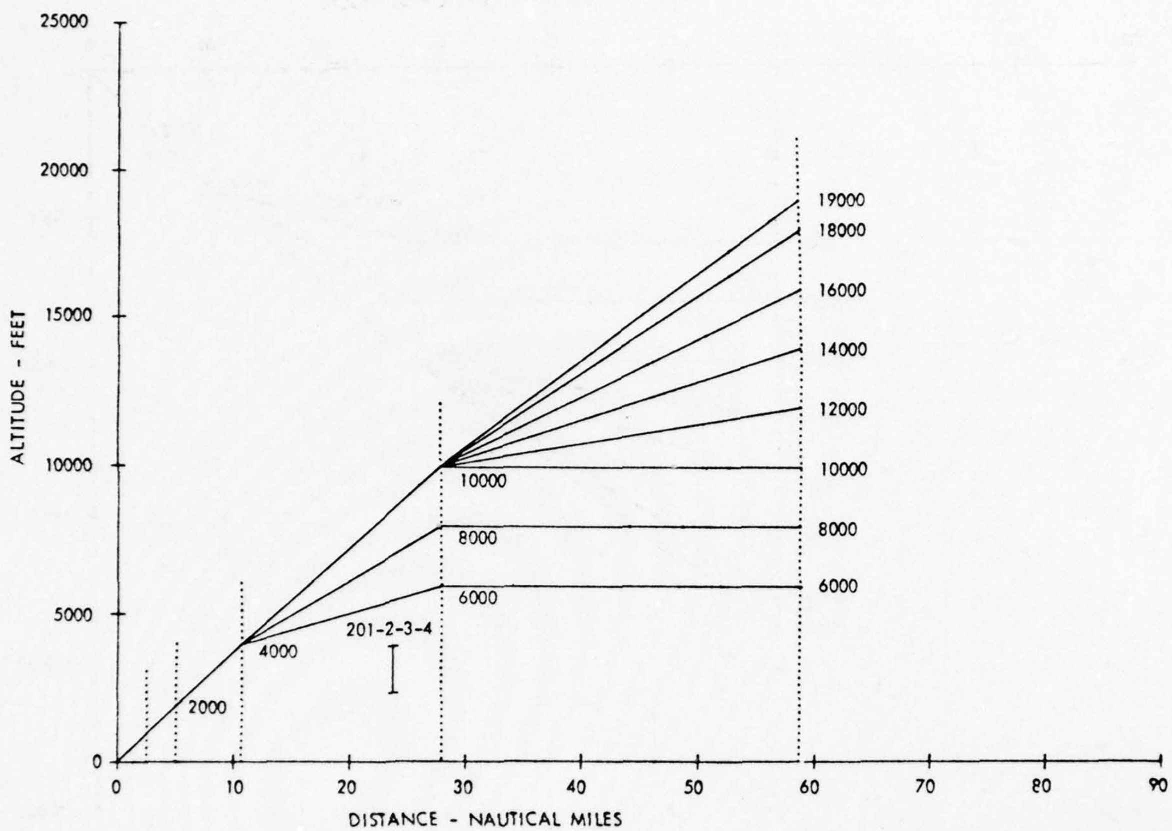
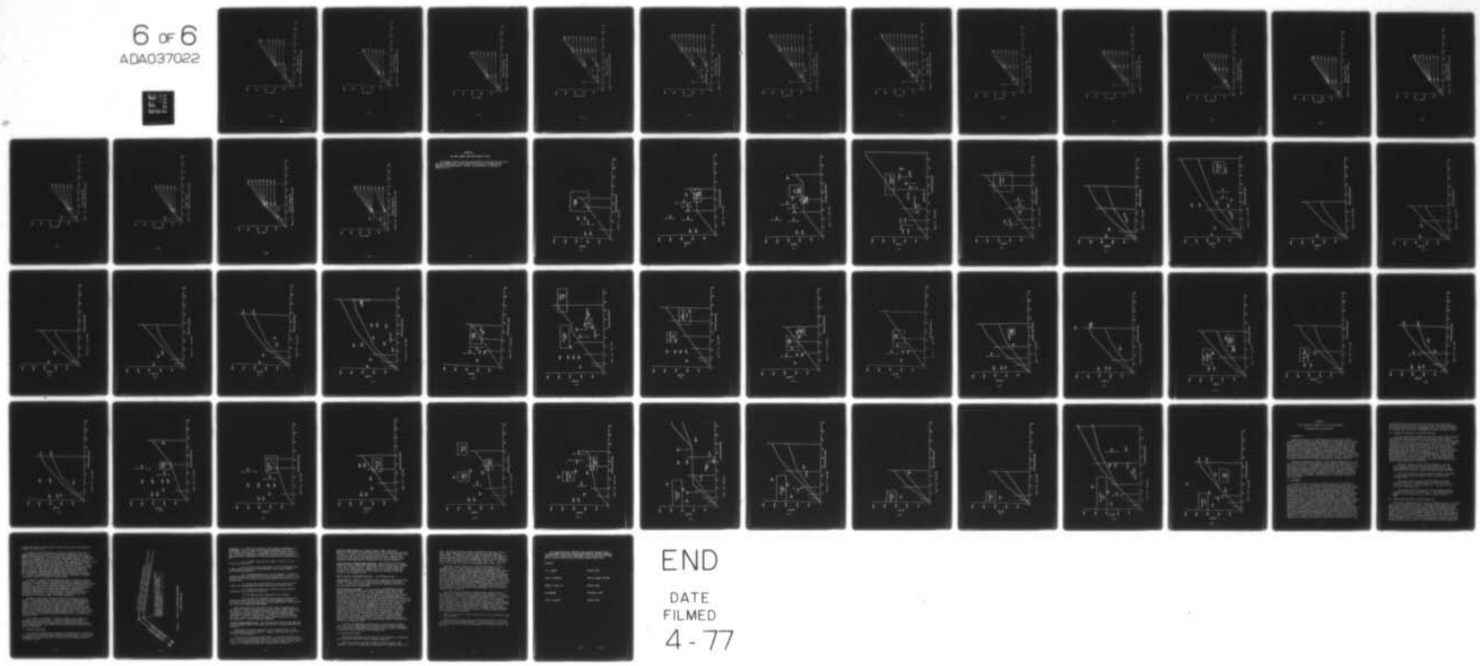


Figure C.10 Departure Route 303, East Flow

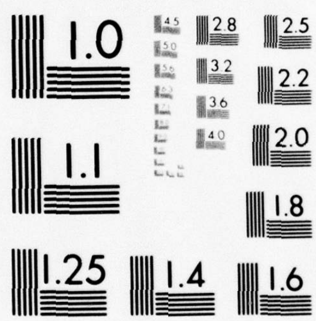
AD-A037 022 CHAMPLAIN TECHNOLOGY INDUSTRIES PALO ALTO CALIF F/G 17/7
TERMINAL AREA DESIGN - ANALYSIS AND VALIDATION OF RNAV TASK FOR--ETC(U)
OCT 75 E D MCCONKEY , W H CLARK DOT-FA72WA-3098

UNCLASSIFIED FAA-RD-76-194 NL

6 OF 6
ADA037022



END
DATE
FILMED
4-77



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

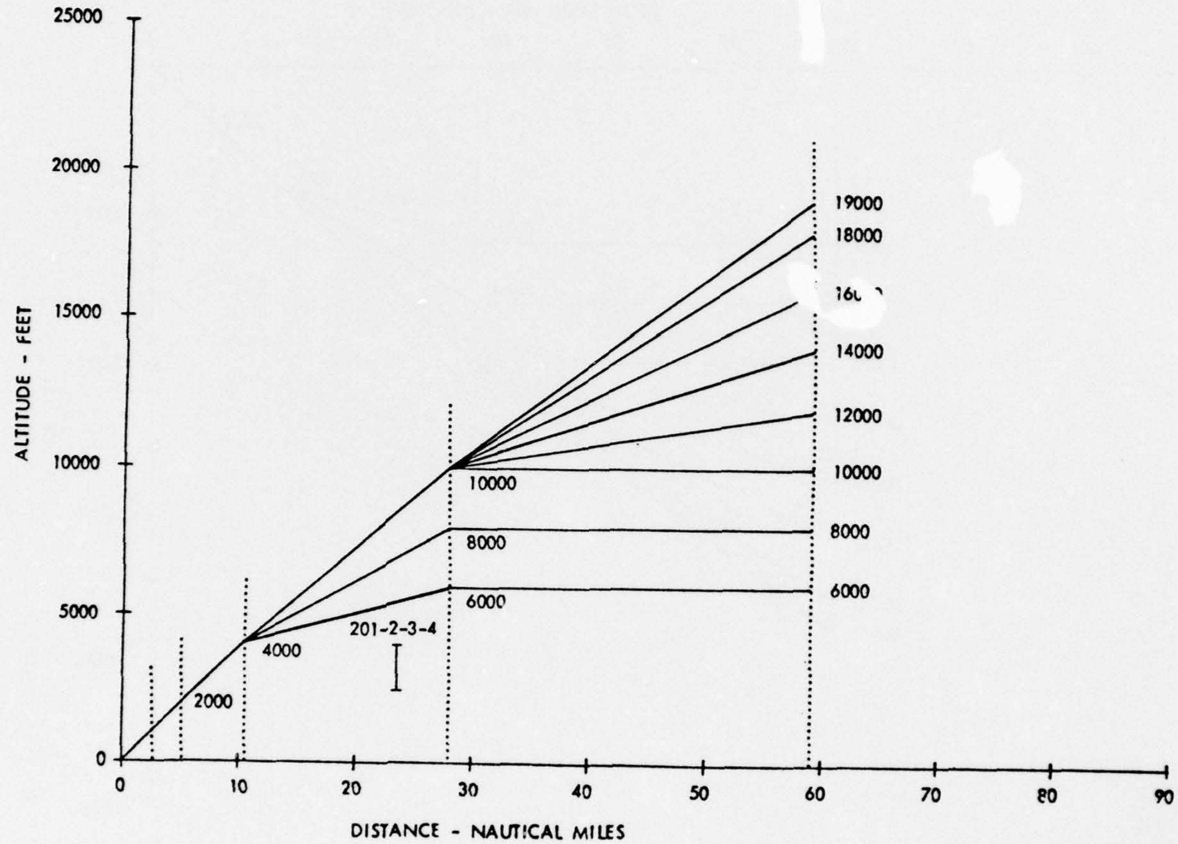


Figure C.11 Departure Route 304, East Flow

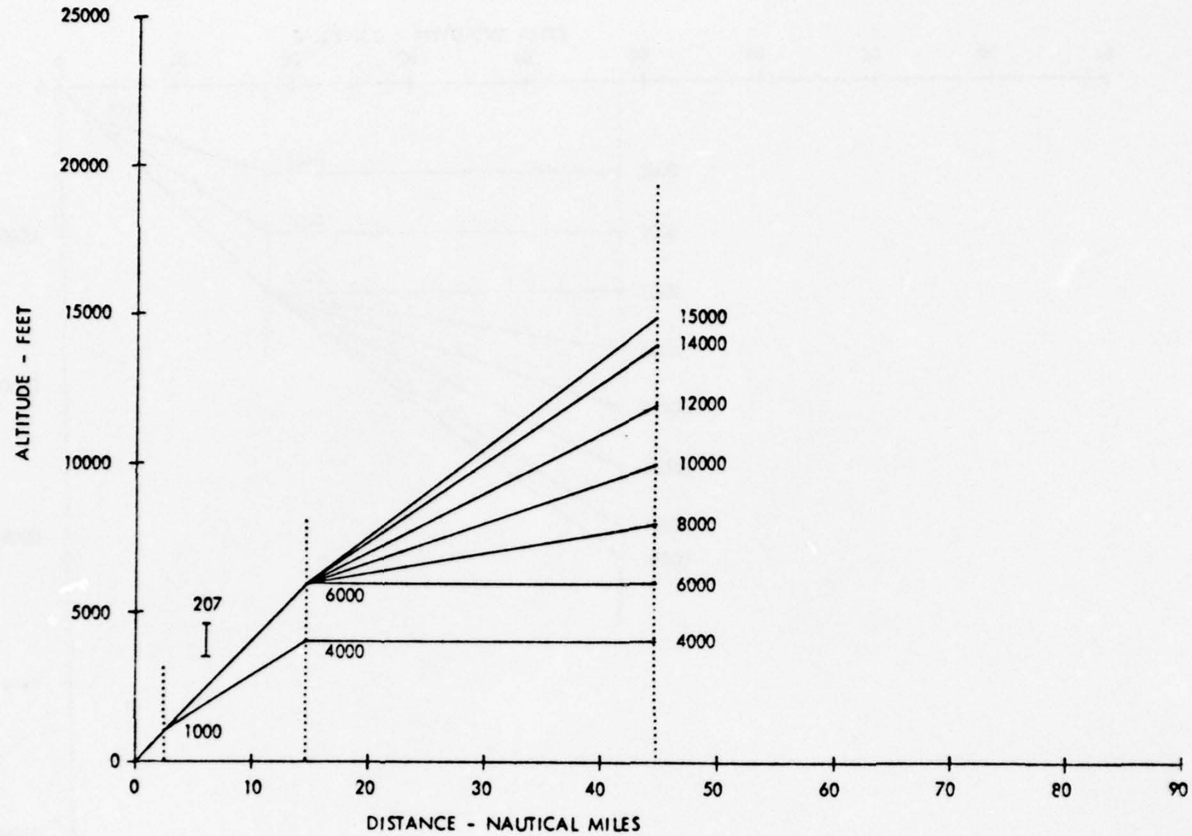


Figure C.12 Departure Route 305, East Flow

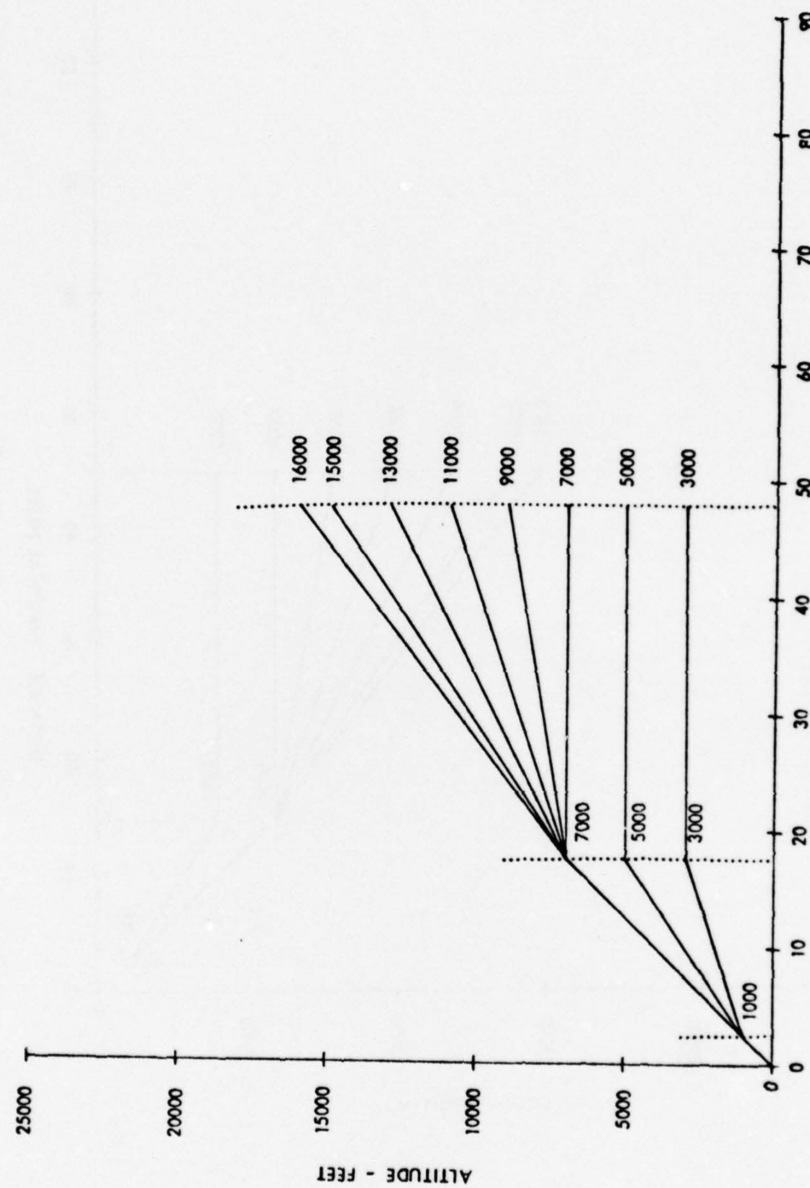


Figure C.13 Departure Route 306, East Flow

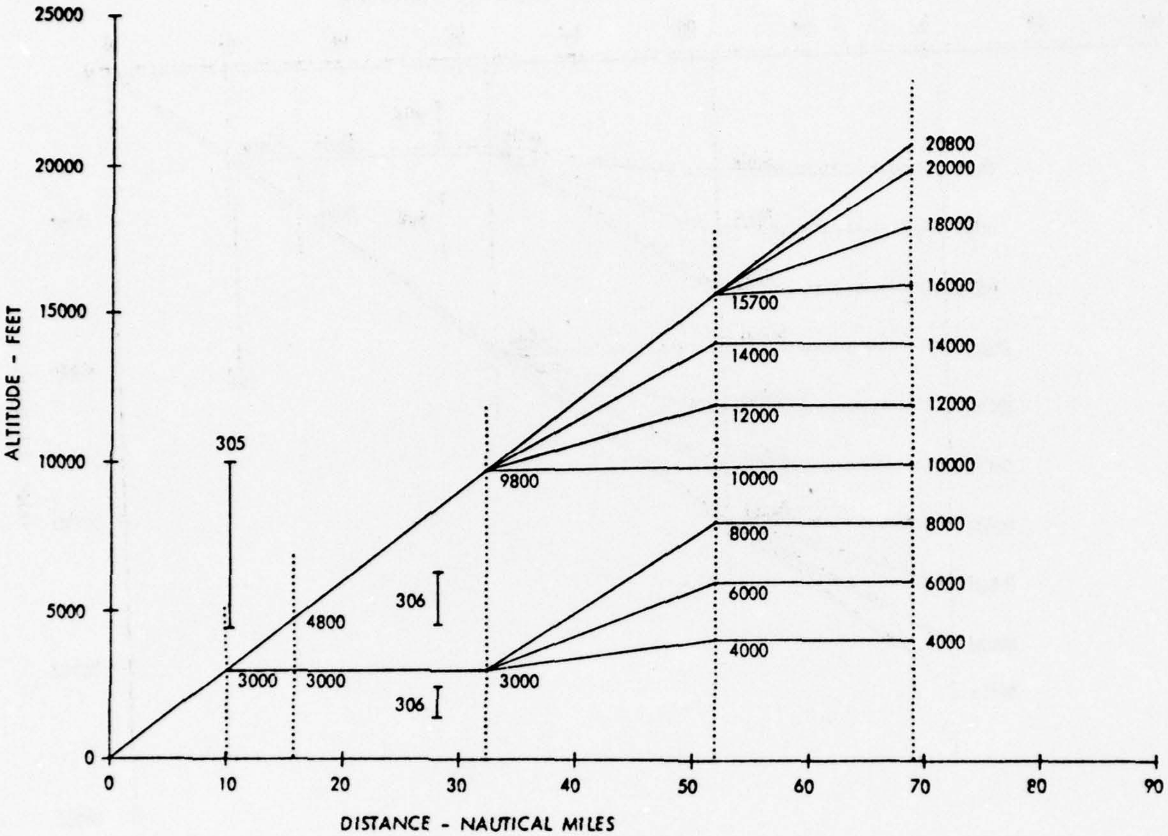


Figure C.14 Arrival Route 201, North Flow

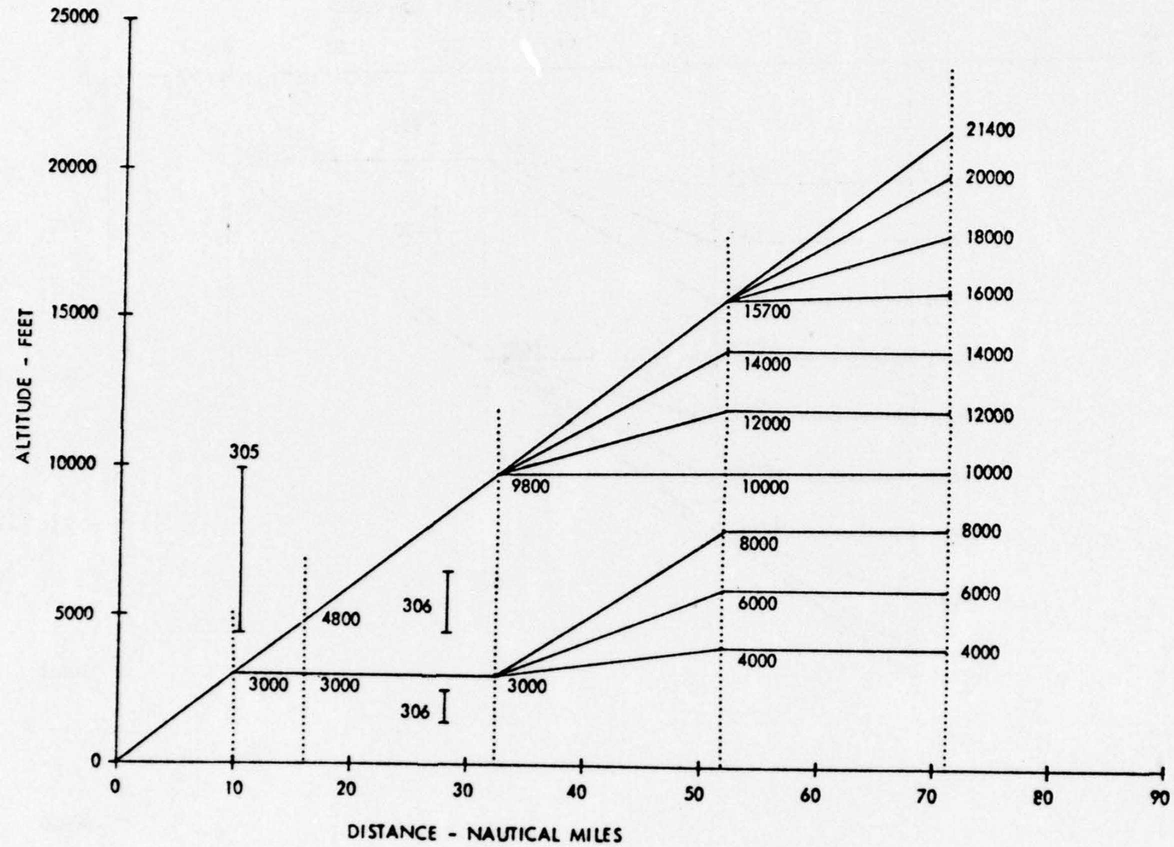


Figure C.15 Arrival Route 202, North Flow

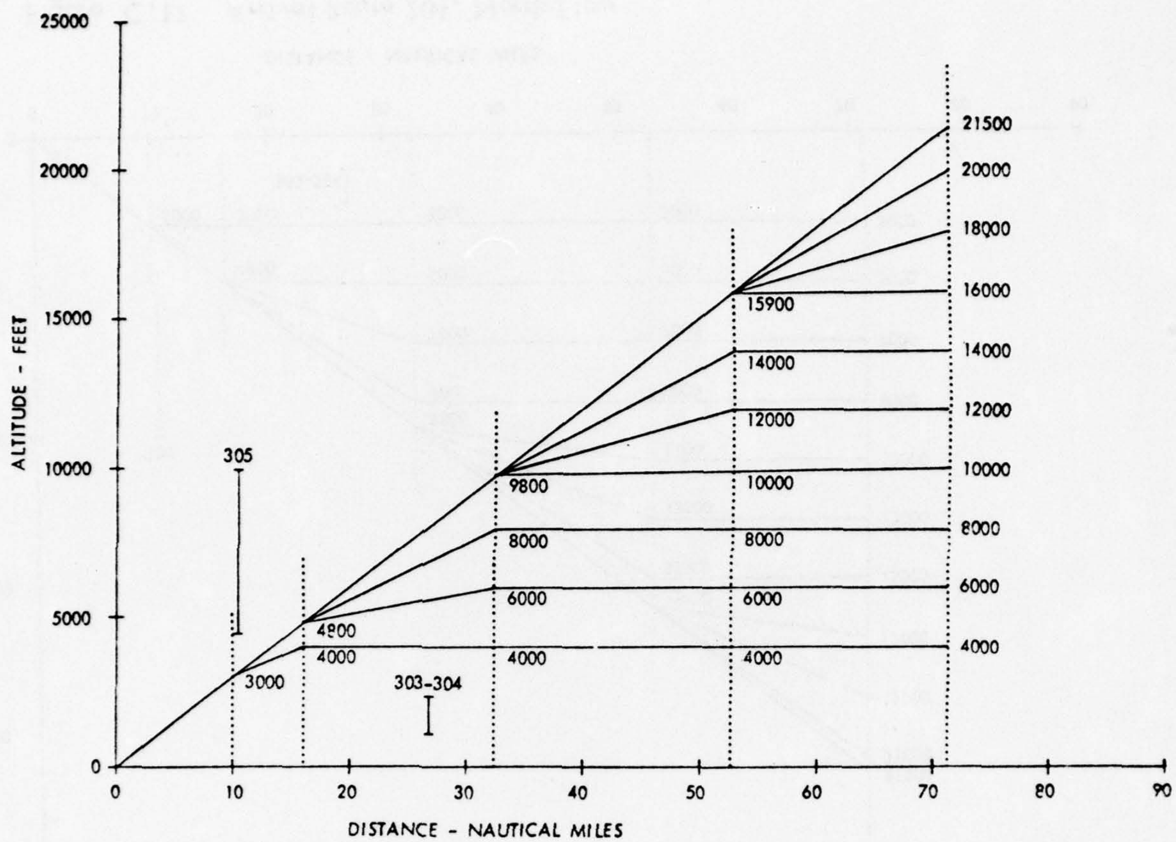


Figure C.16 Arrival Route 203, North Flow

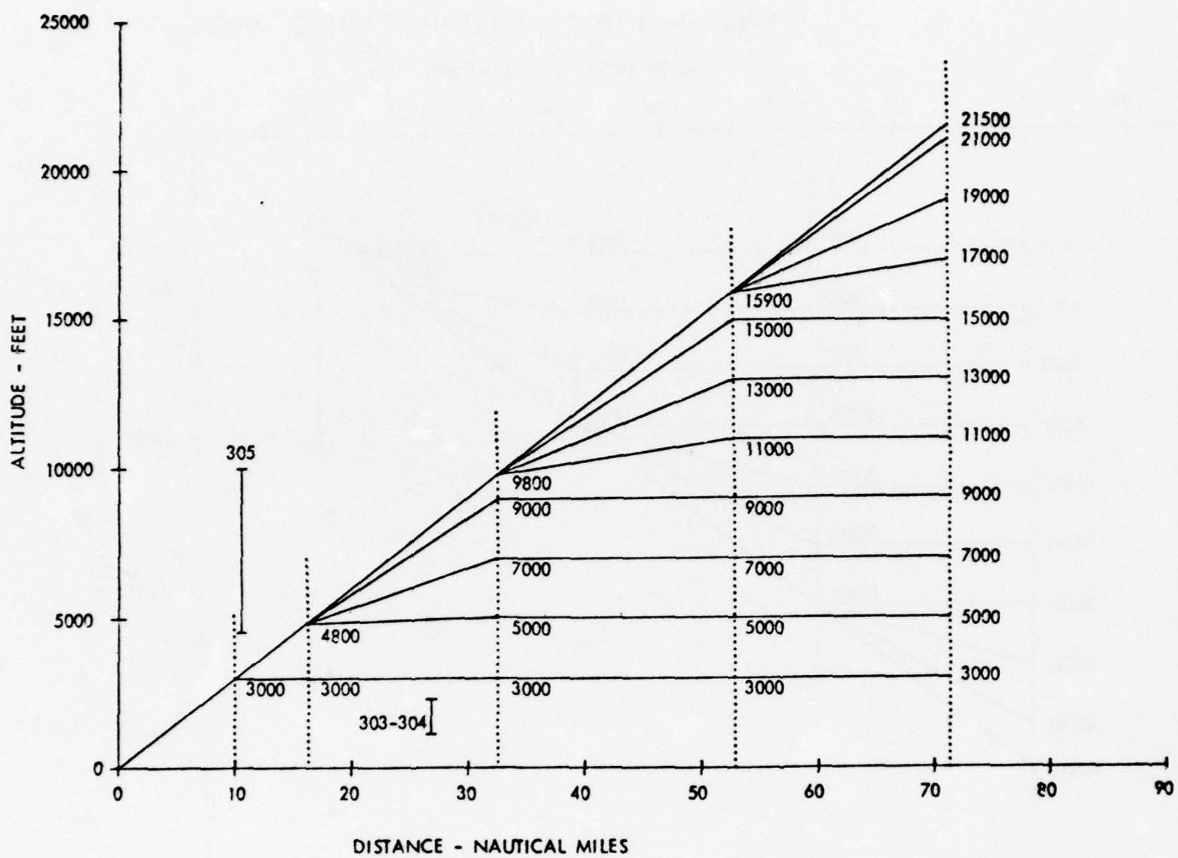


Figure C.17 Arrival Route 204, North Flow

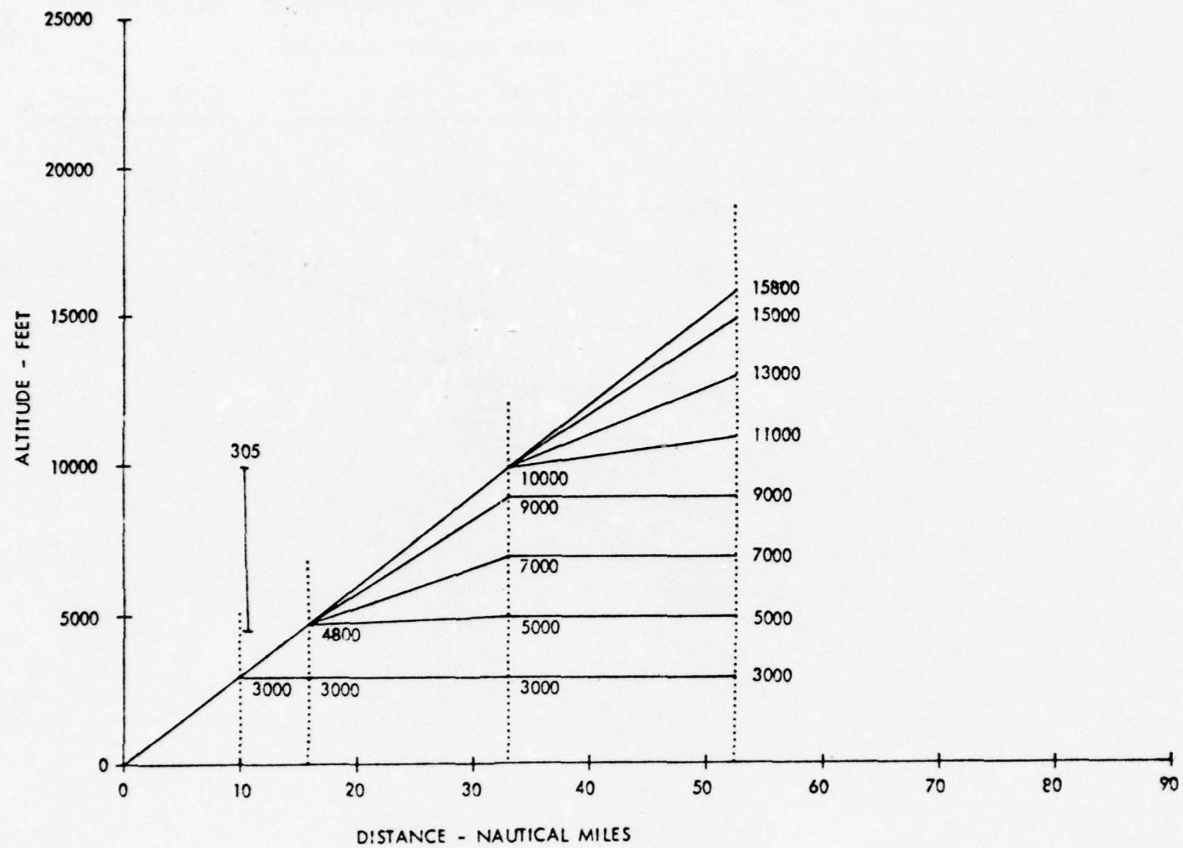


Figure C.18 Arrival Route 205, North Flow

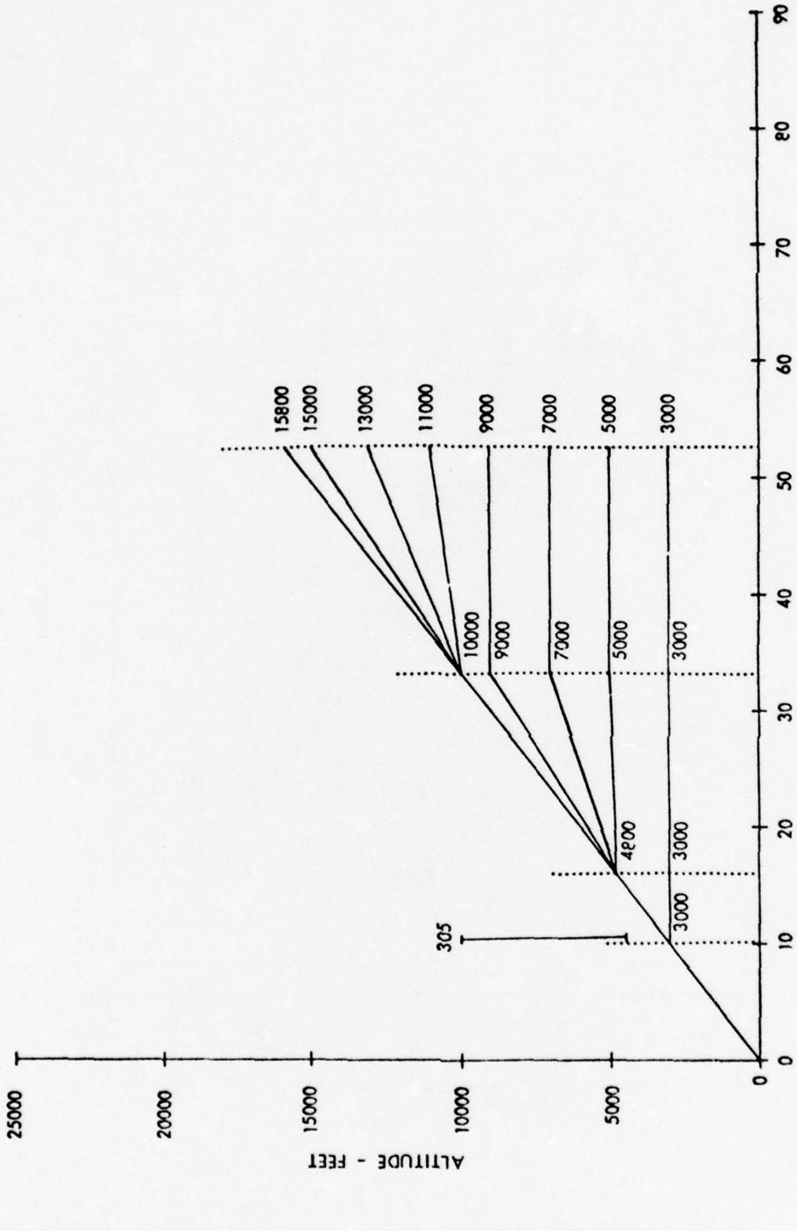


Figure C.19 Arrival Route 206, North Flow

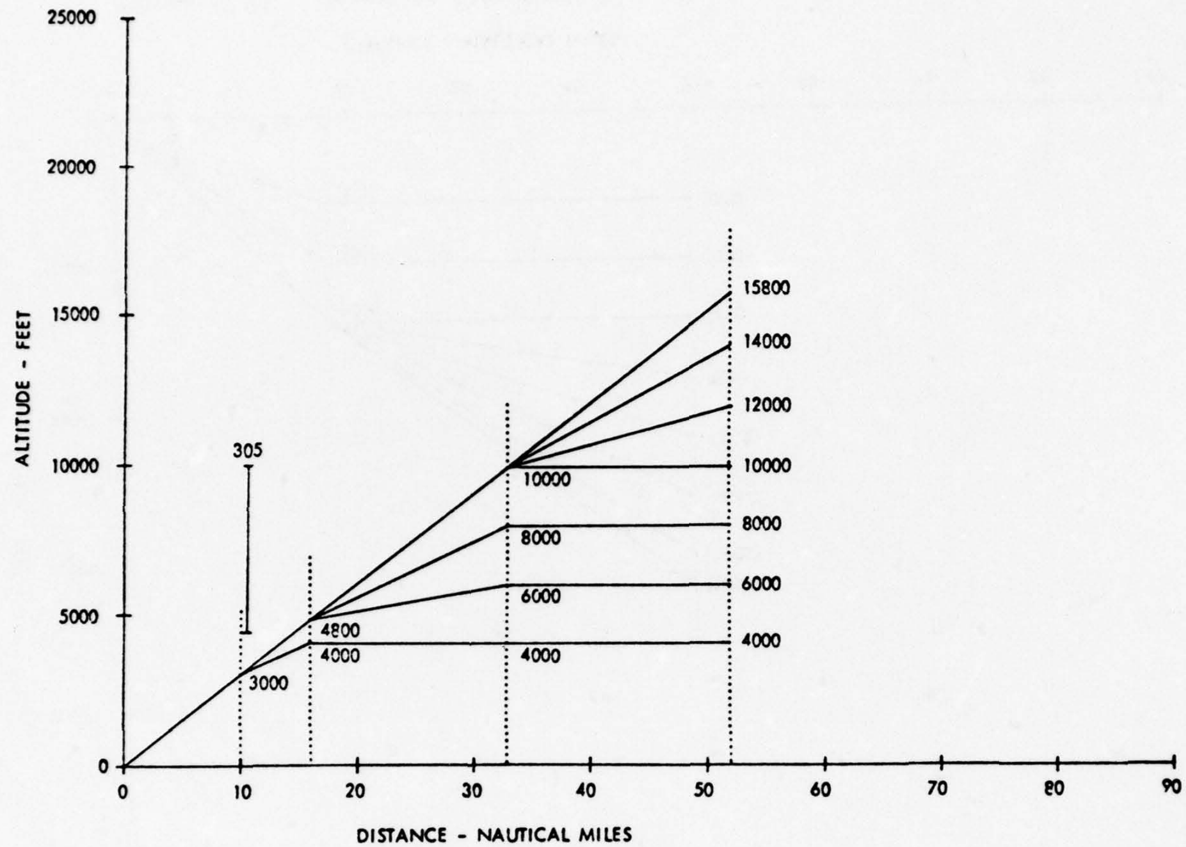


Figure C.20 Arrival Route 207, North Flow

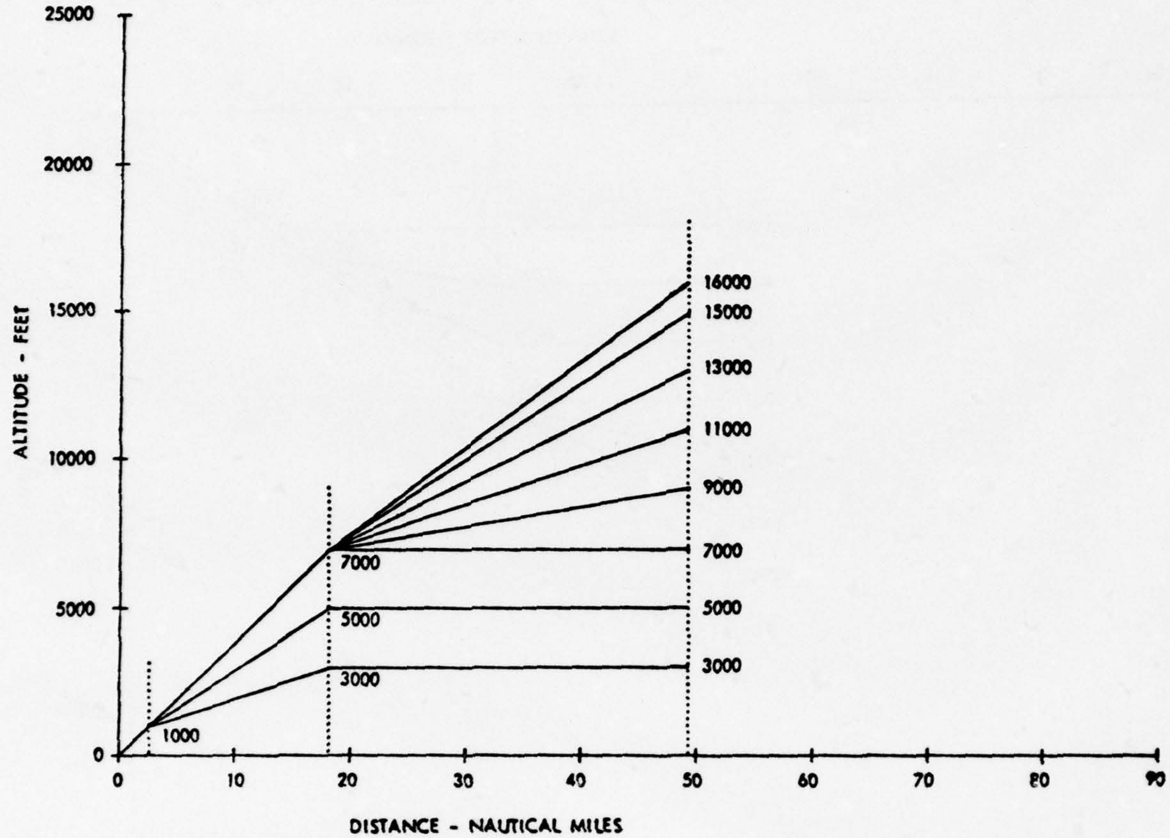


Figure C.21 Departure 301, North Flow

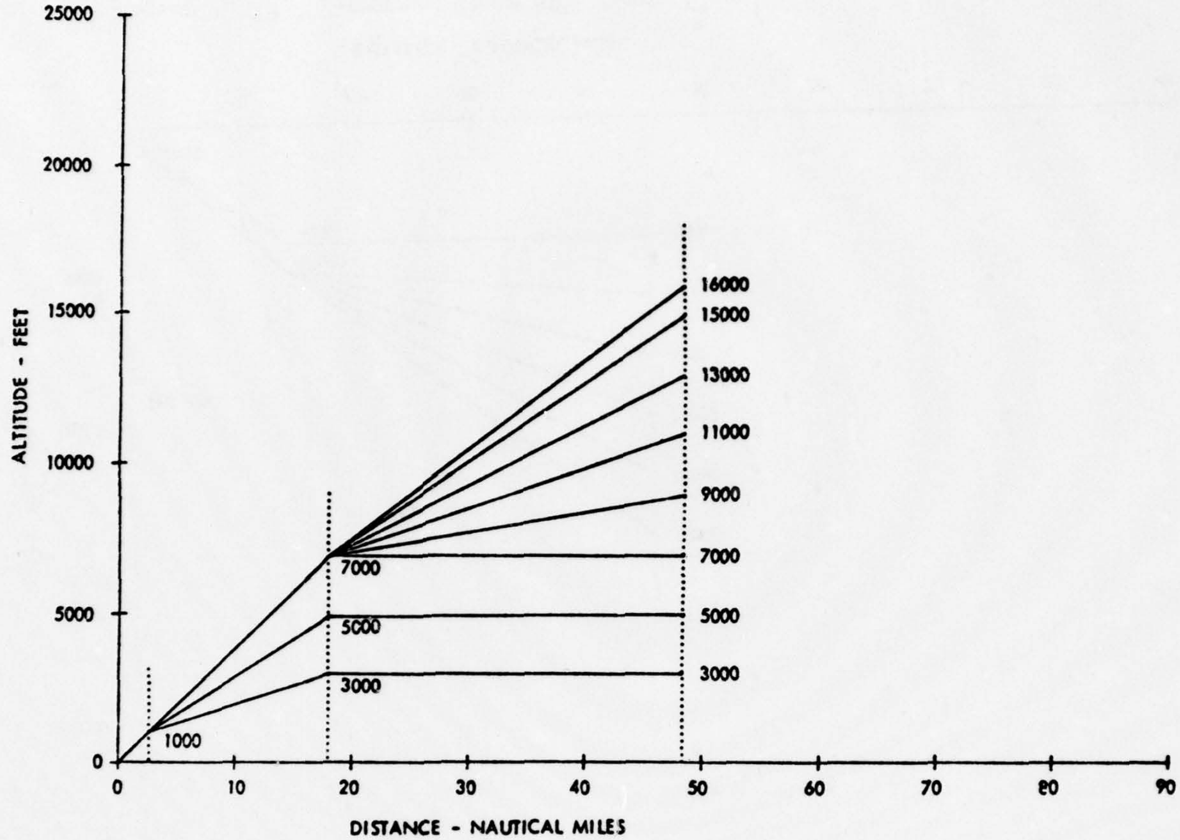


Figure C.22 Departure Route 302, North Flow

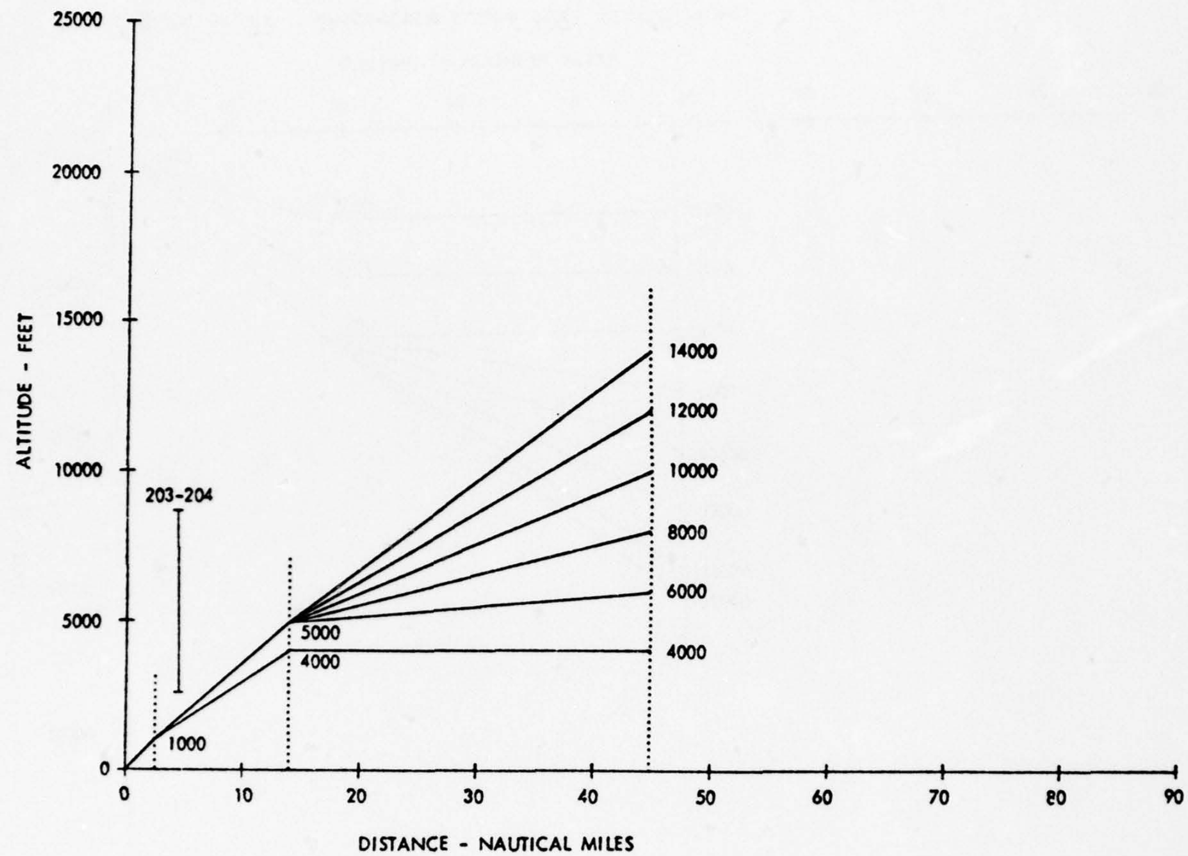


Figure C.23 Departure Route 303, North Flow

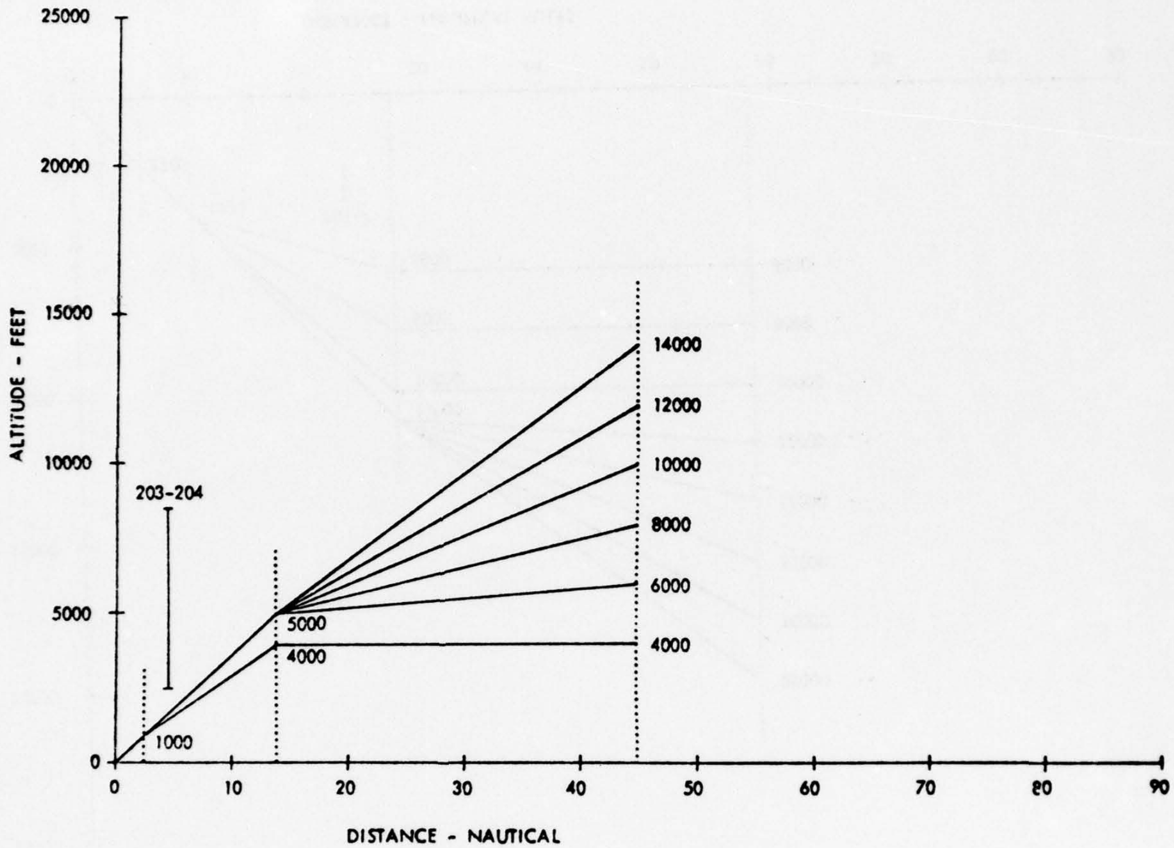


Figure C.24 Departure Route 304, North Flow

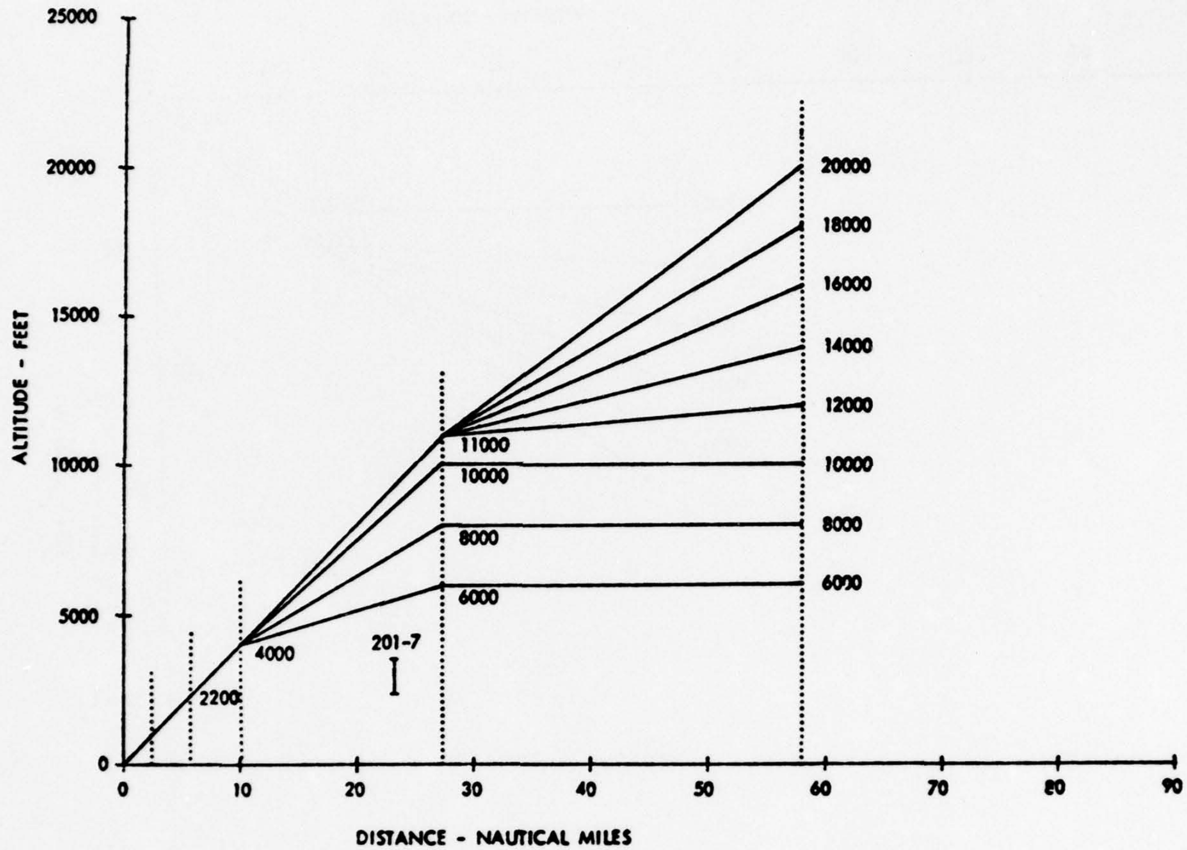


Figure C.25 Departure Route 305, North Flow

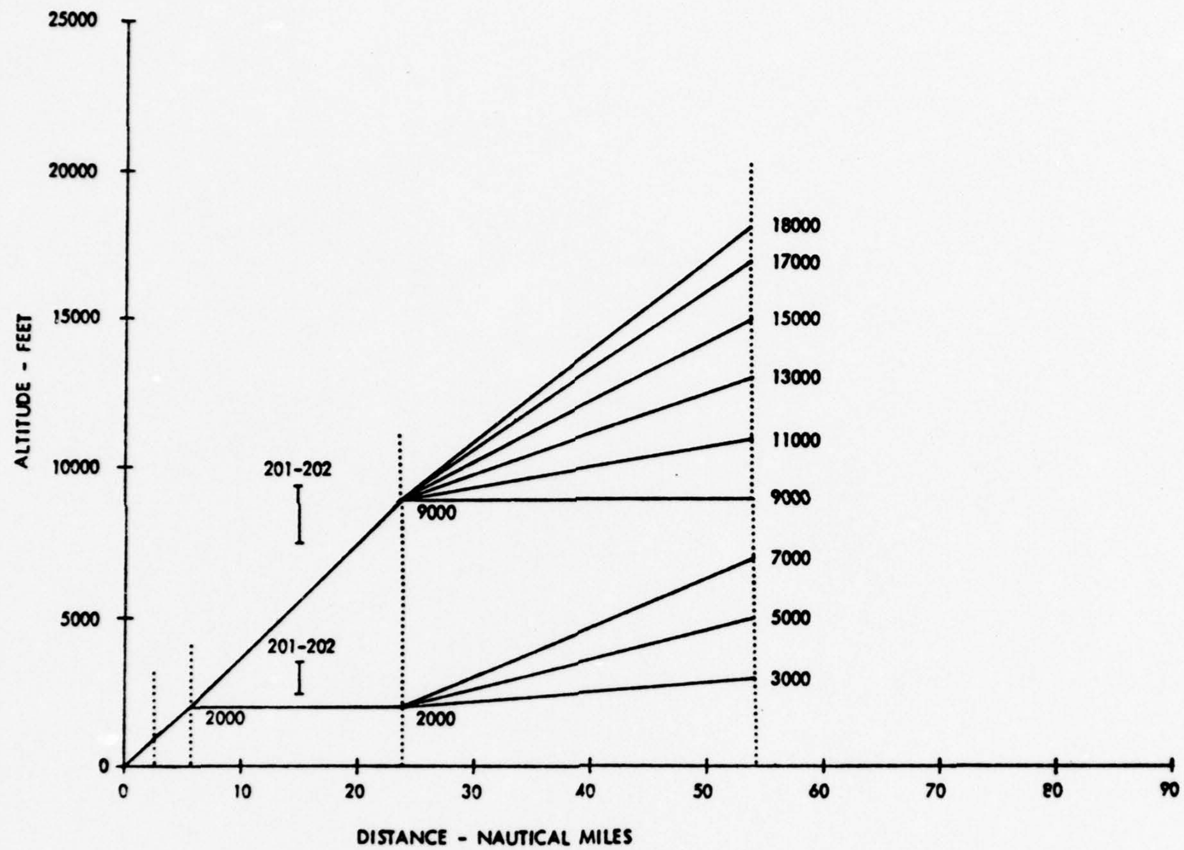


Figure C.26 Departure Route 306, North Flow

APPENDIX D

NEW YORK TERMINAL AREA VNAV ENVELOPE DESIGN

This appendix contains vertical route profiles for the modified post-1982 New York terminal area. These profiles are based upon the VNAV envelope approach to 3D route design. The basic route structure is presented in Section 7.4.3.3.

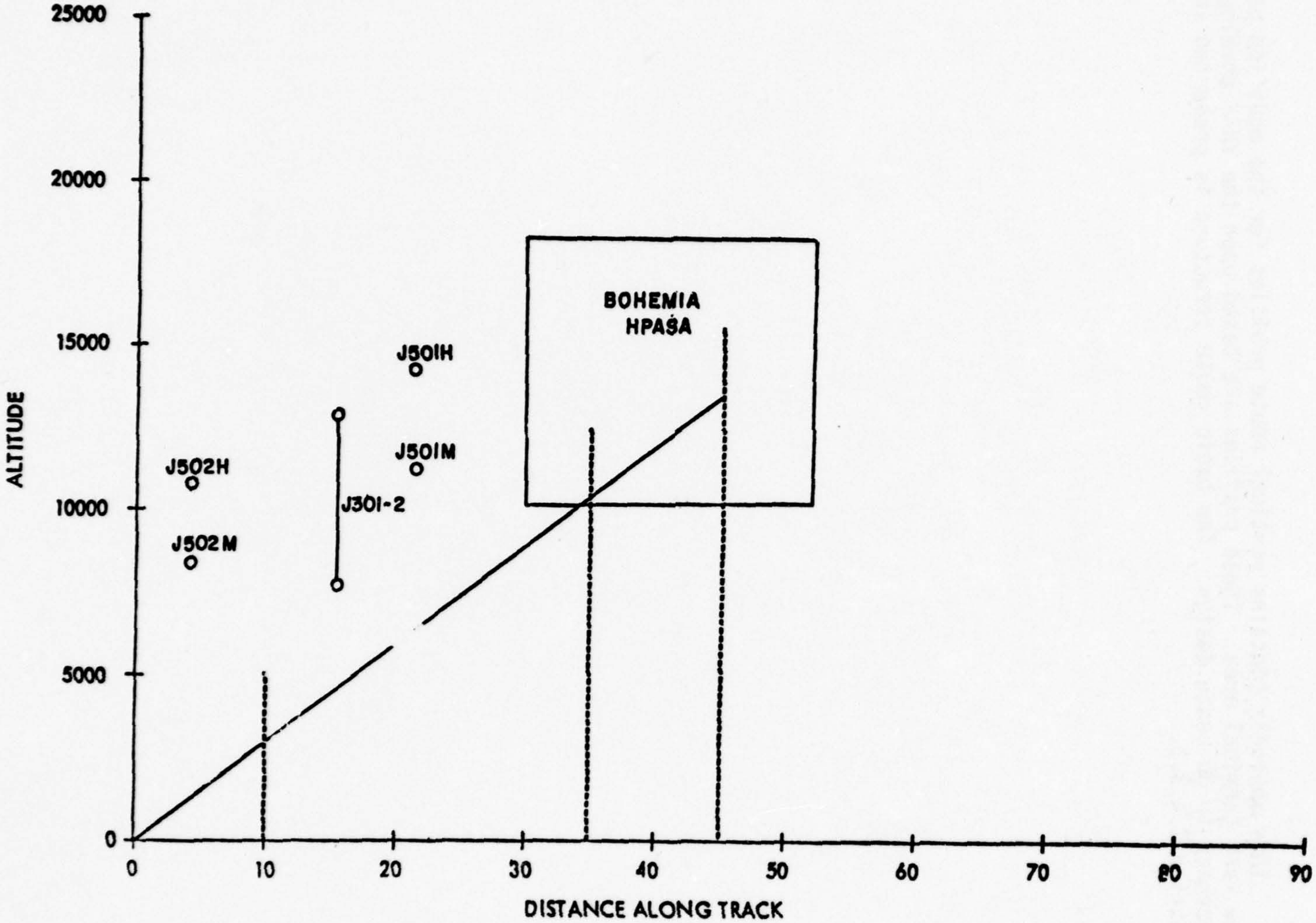


Figure D.1 Route J201

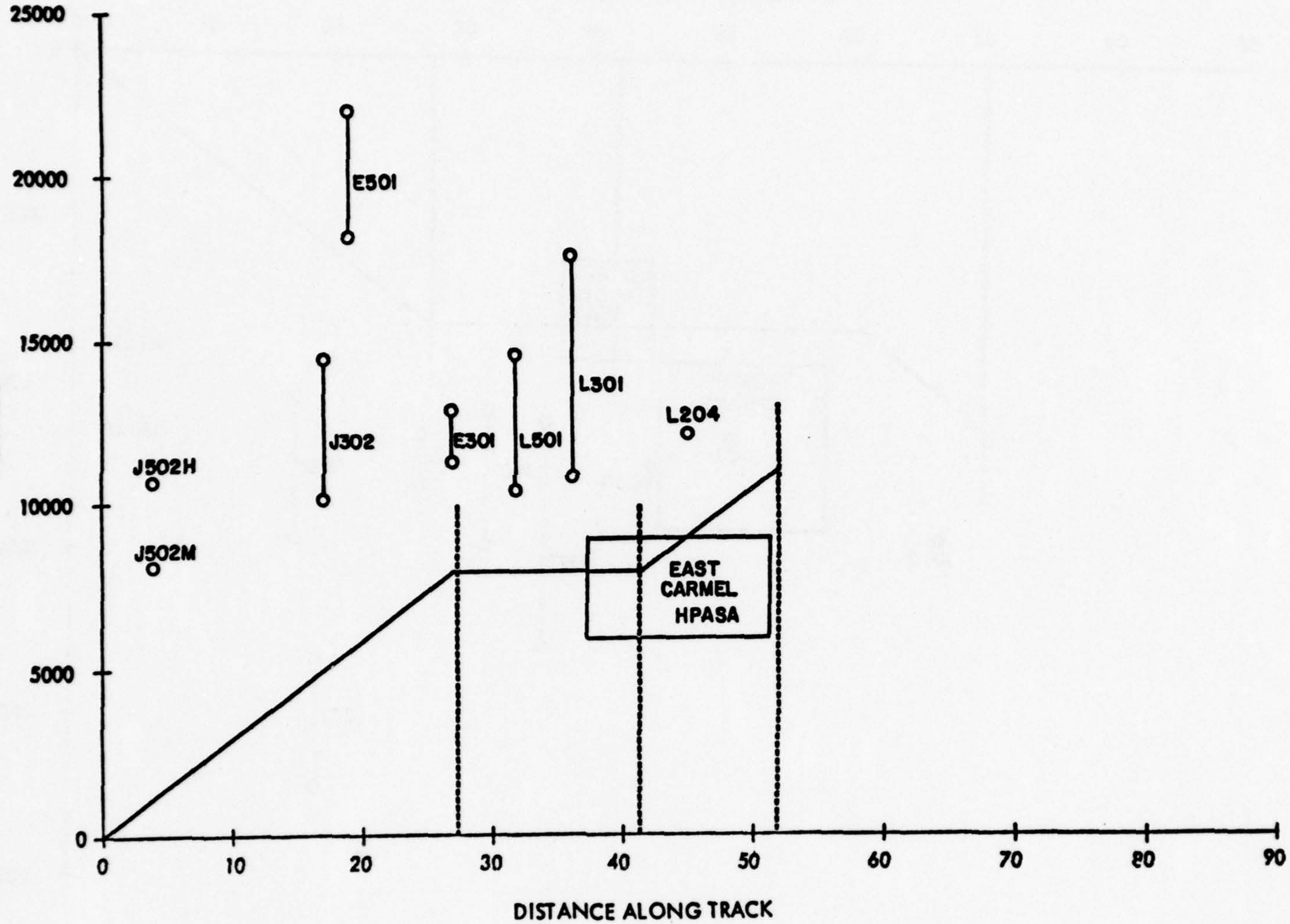


Figure D.2 Route J202

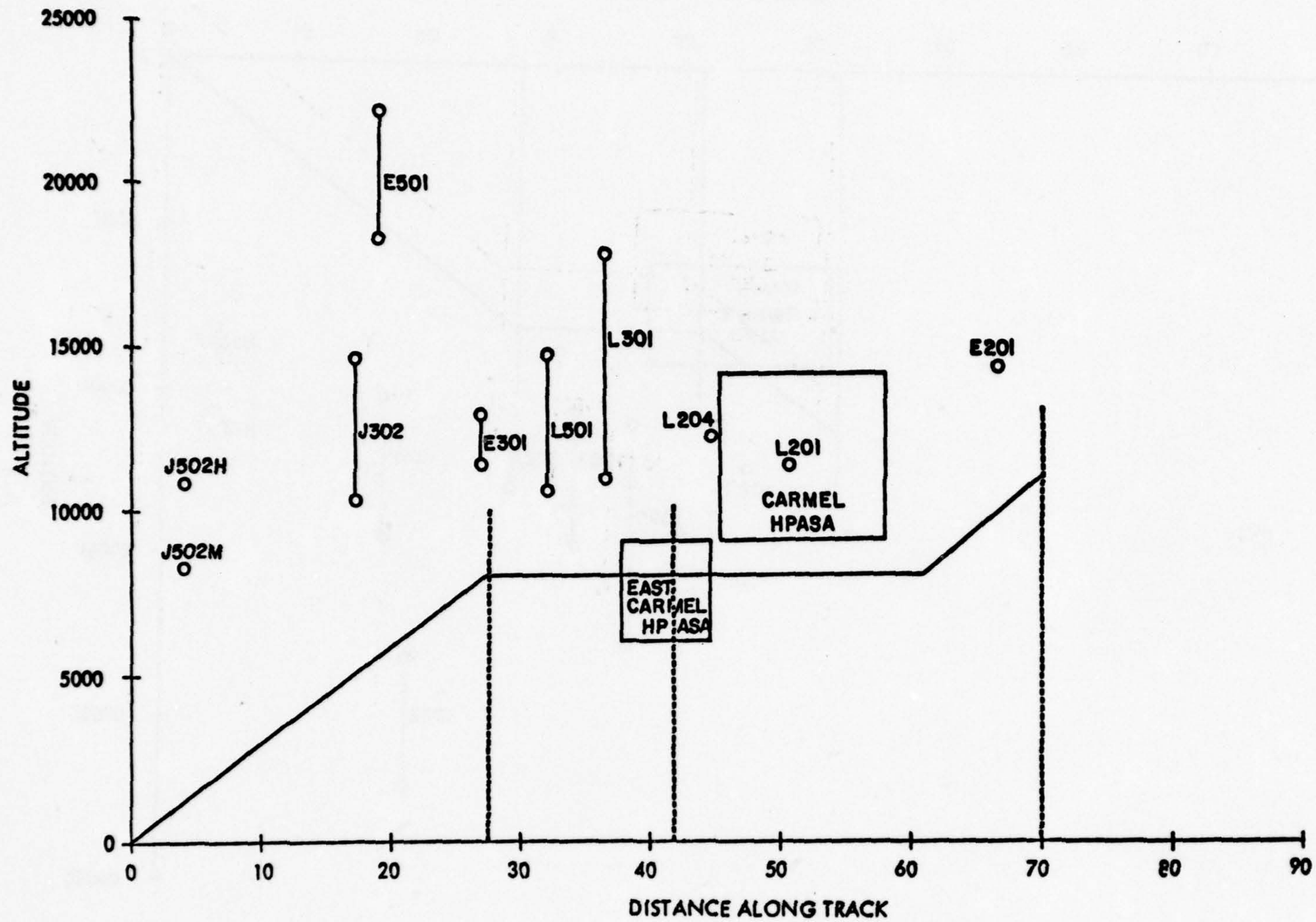


Figure D.3 Route J203

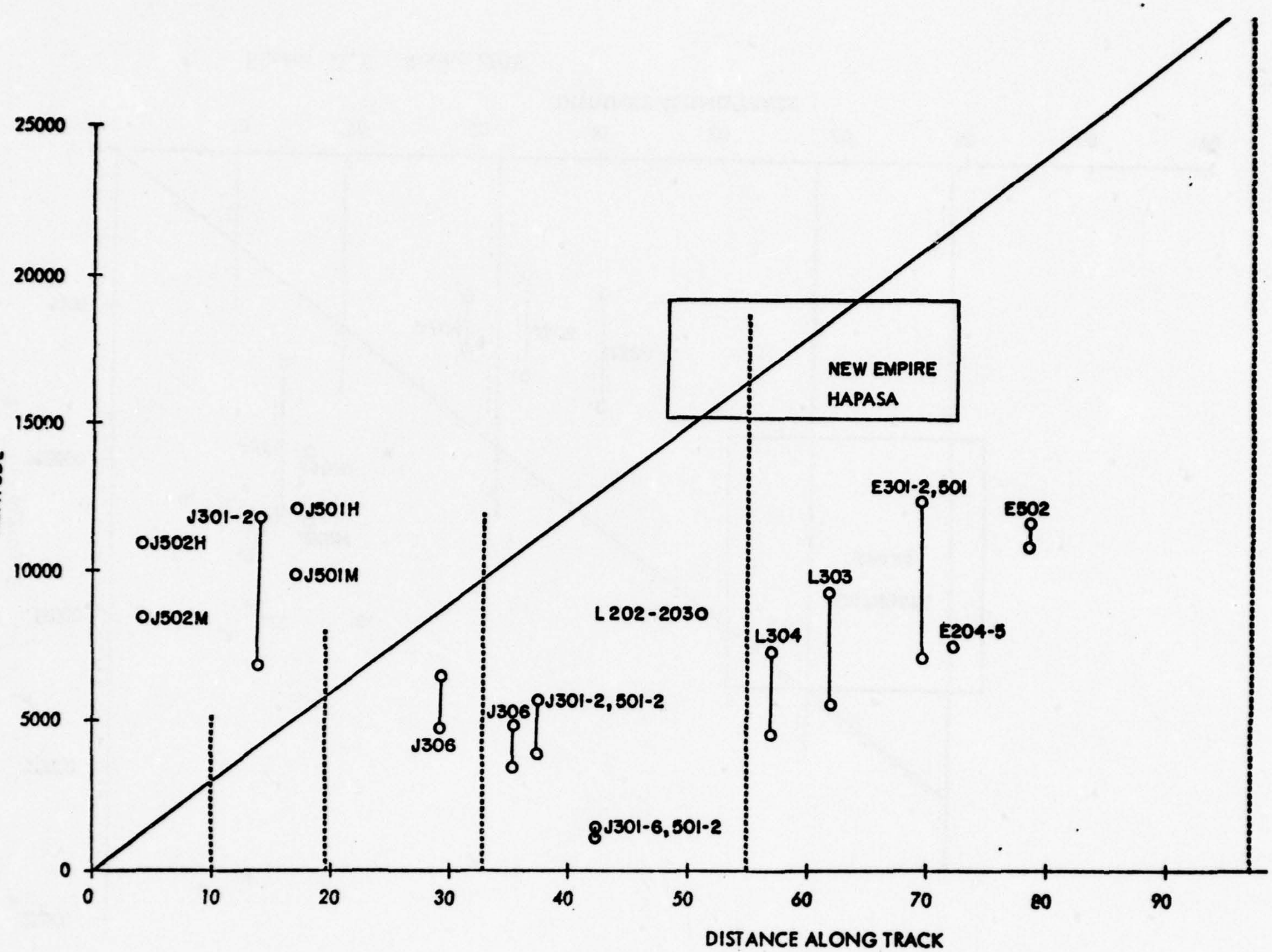


Figure D.4 Route J204

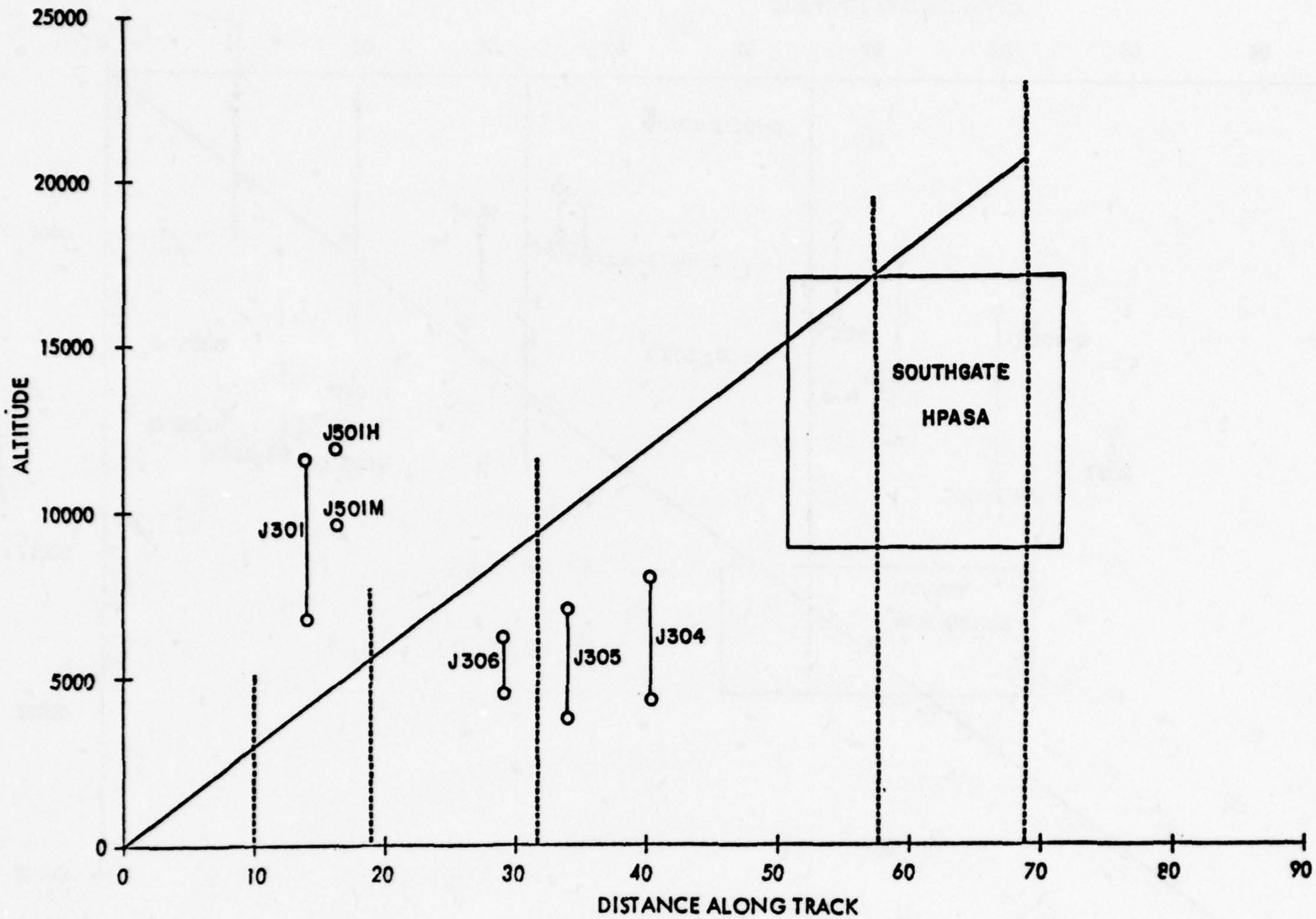


Figure D.5 Route J205

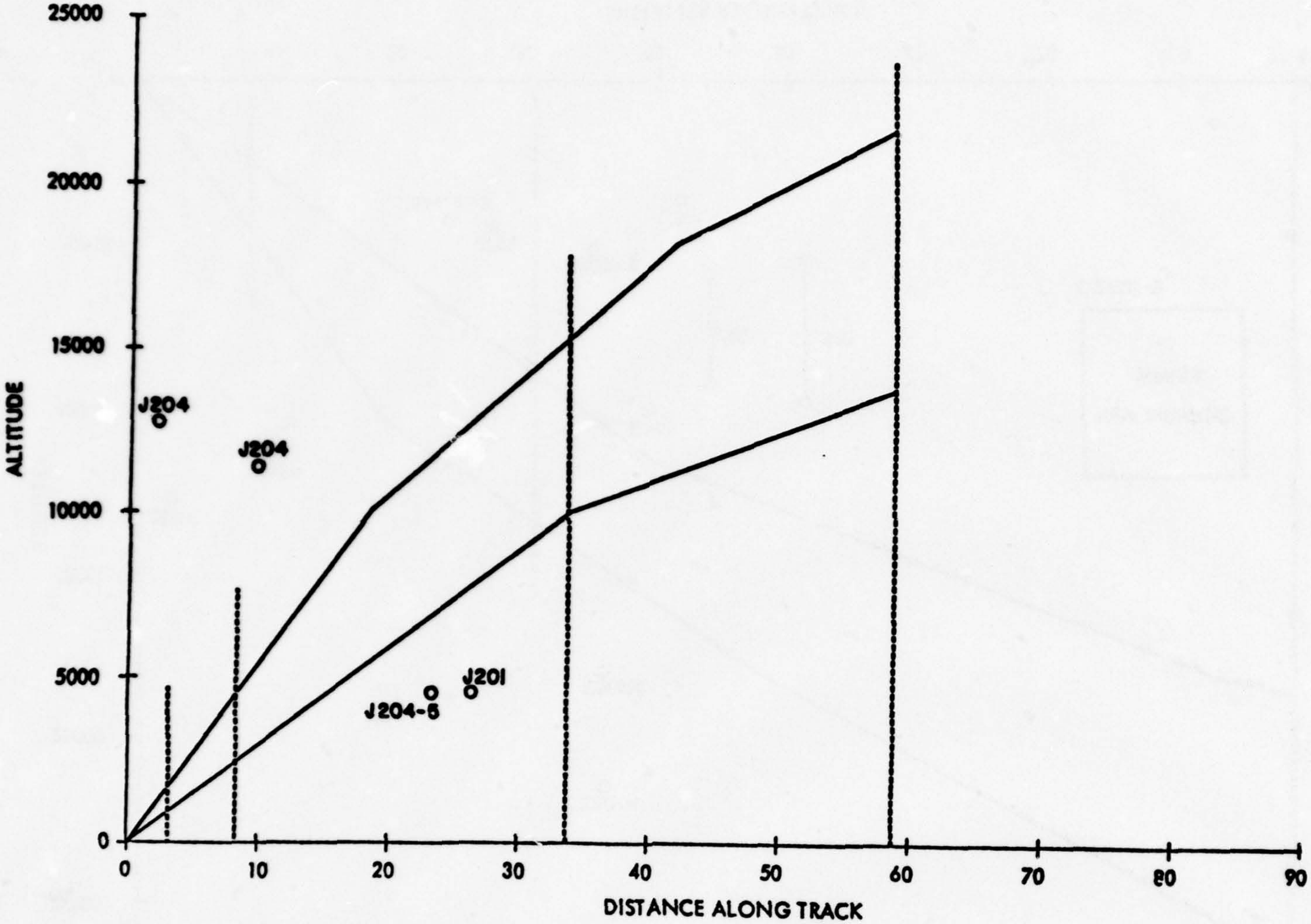


Figure D.6 Route J301

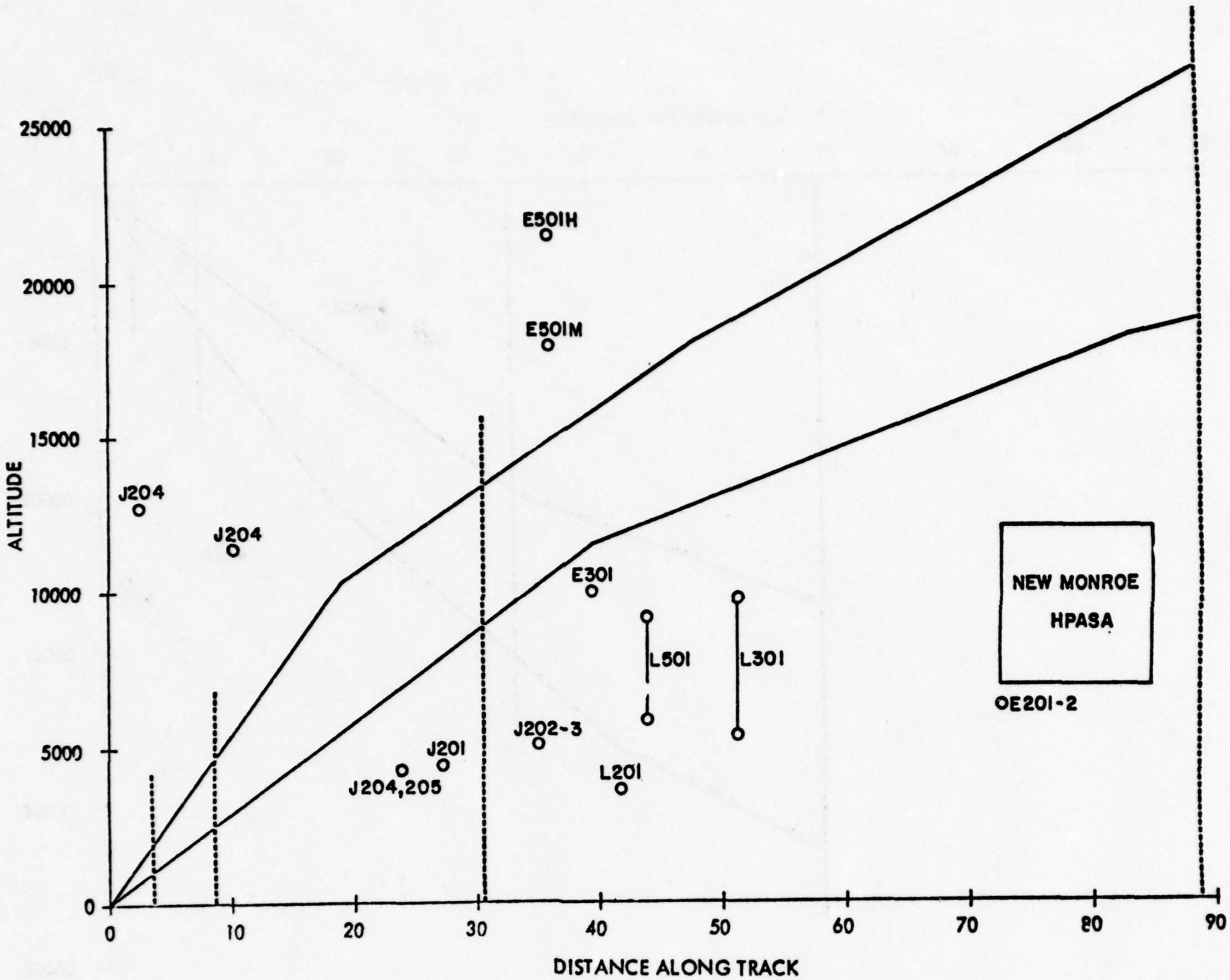


Figure D.7 Route J302

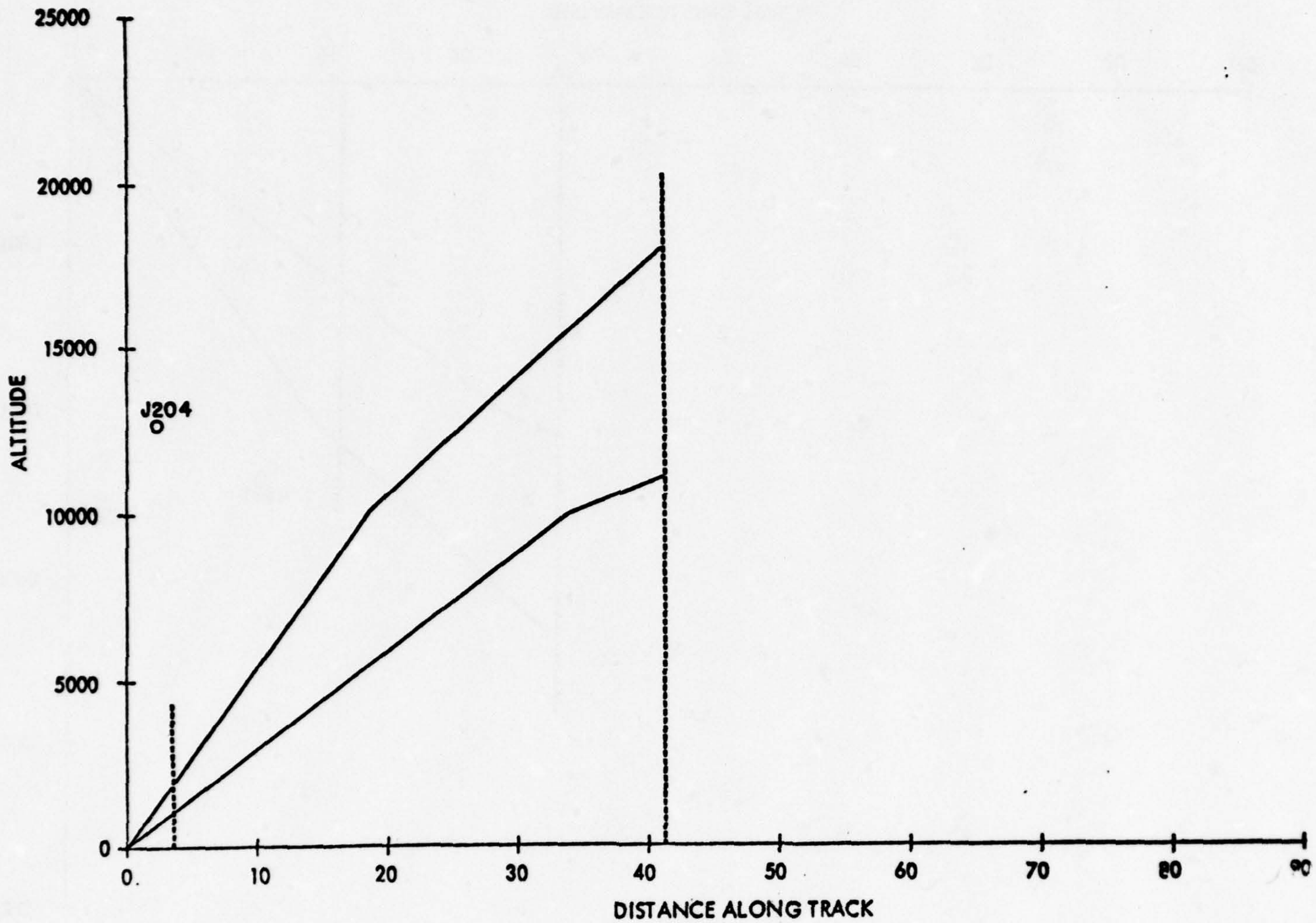


Figure D.8 Route J303

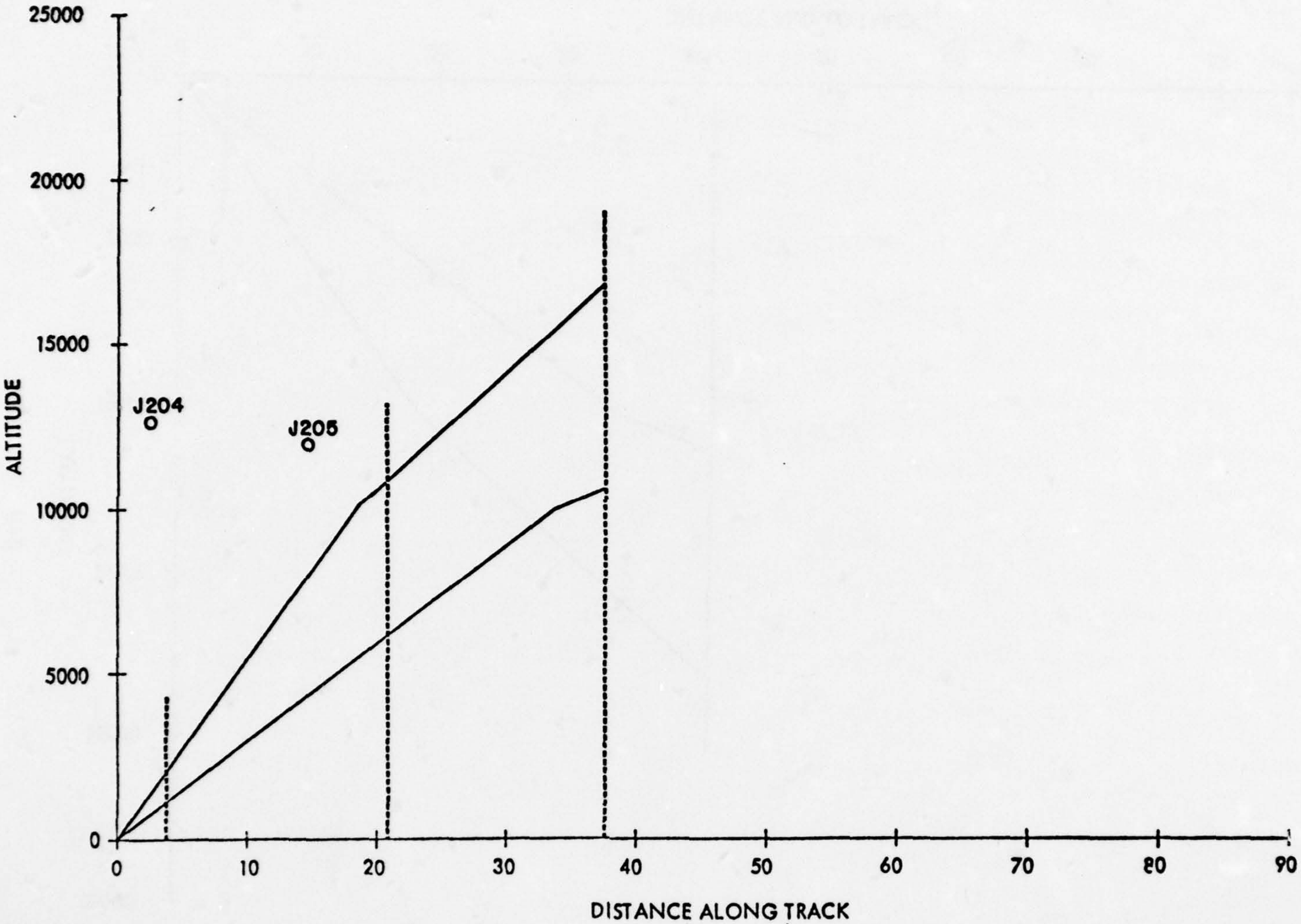


Figure D.9 Route J304

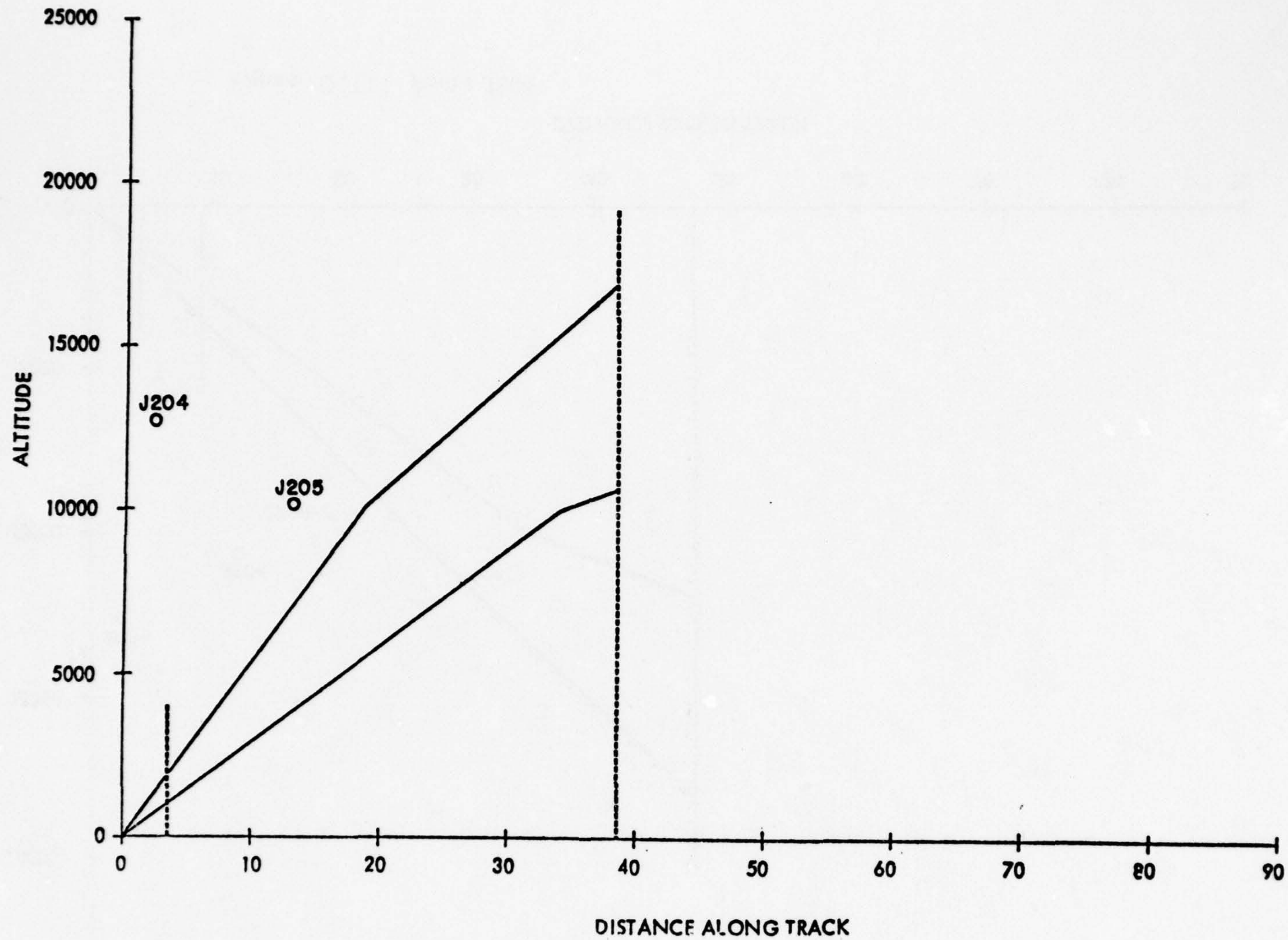


Figure D.10 Route J305

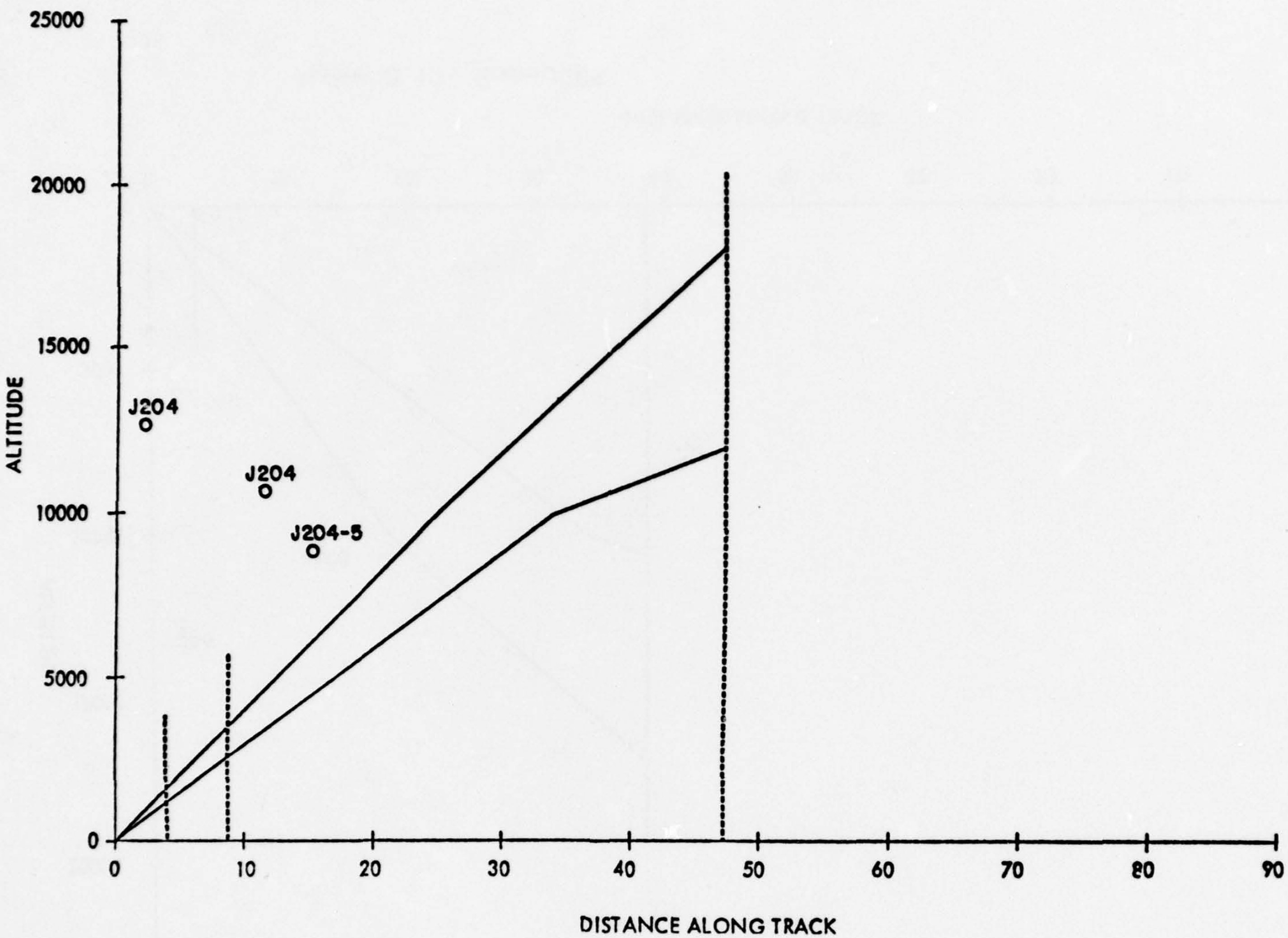


Figure D.11 Route J306

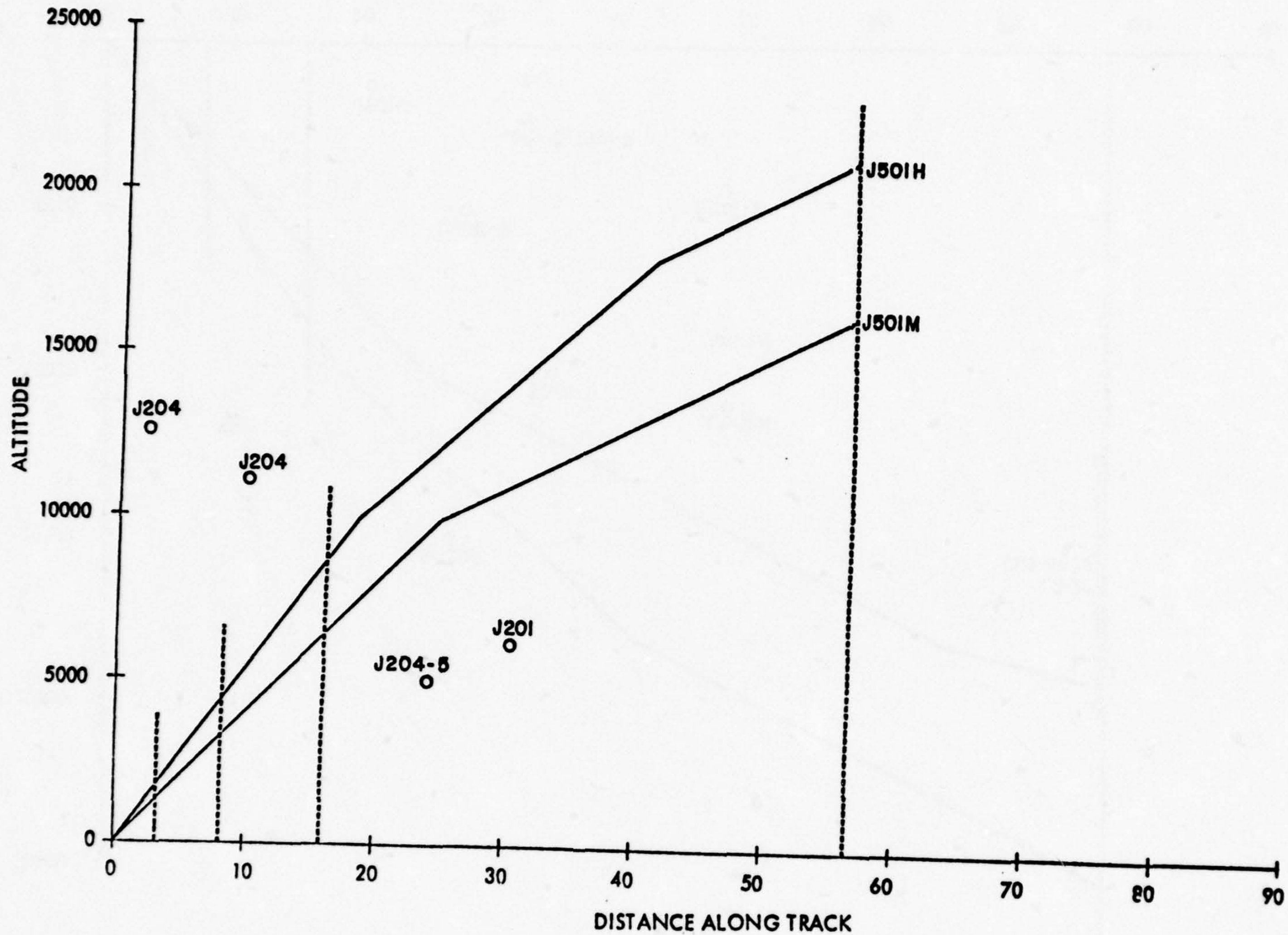


Figure D.12 Route J501

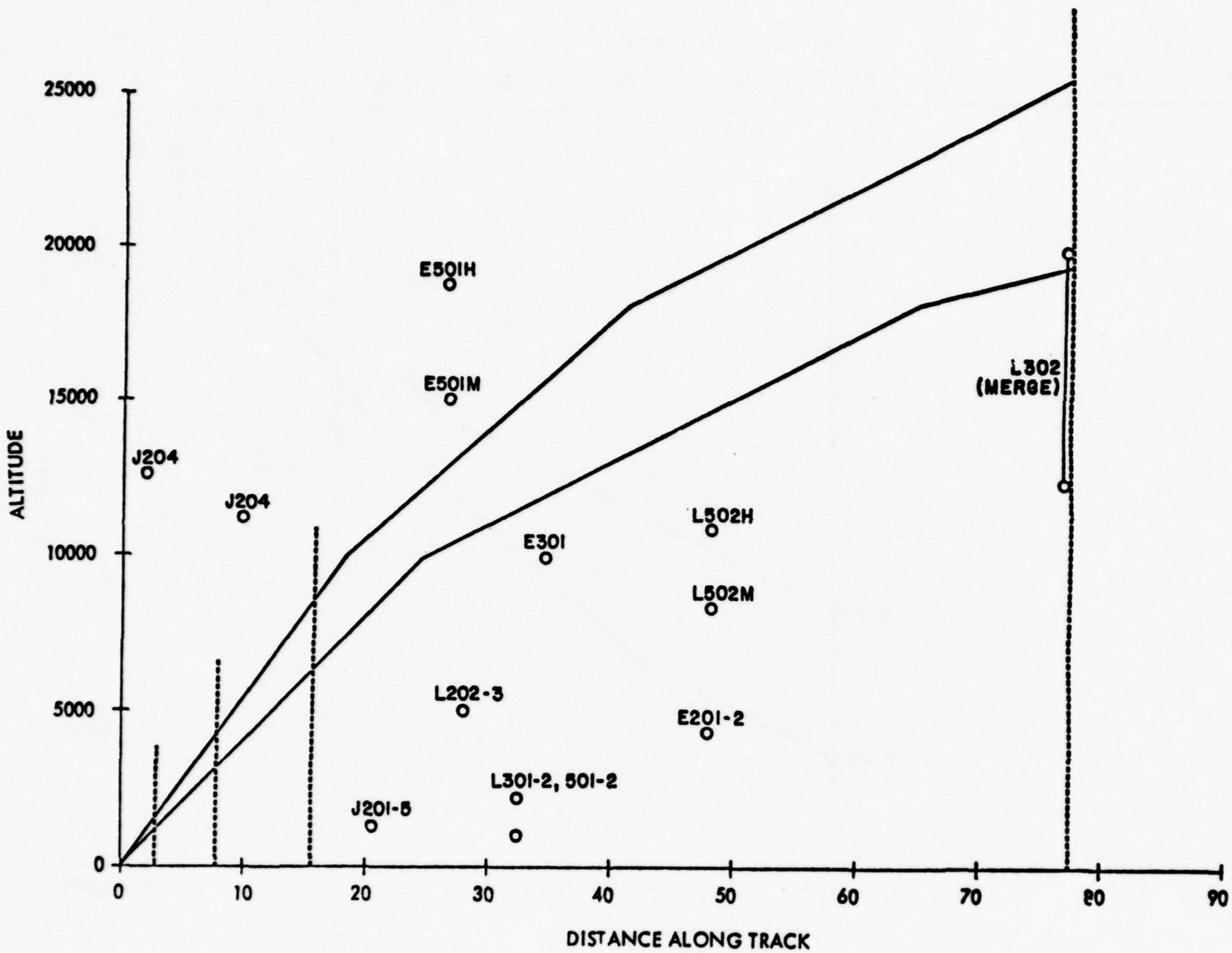


Figure D.13 Route J502

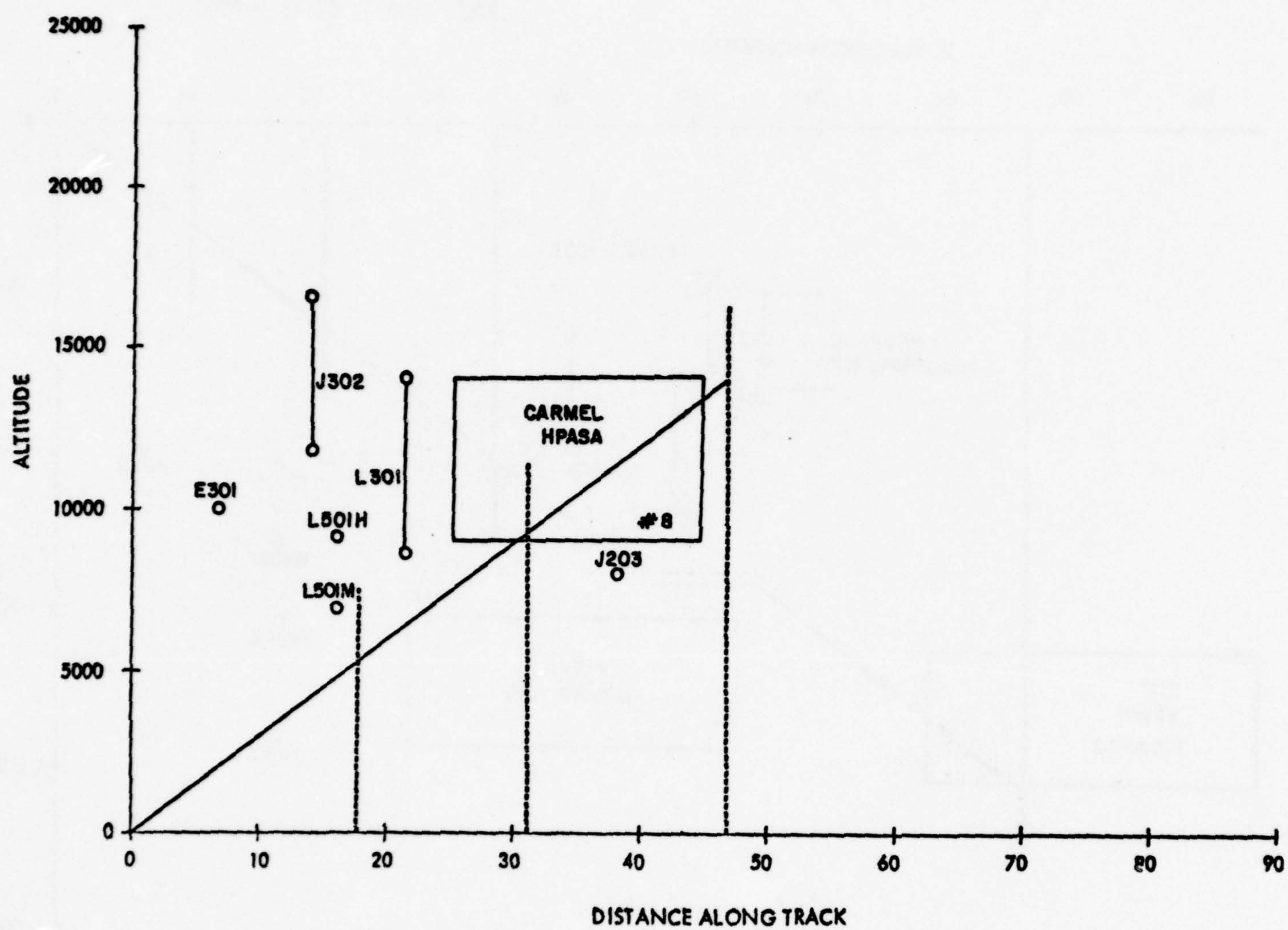


Figure D.14 Route L201

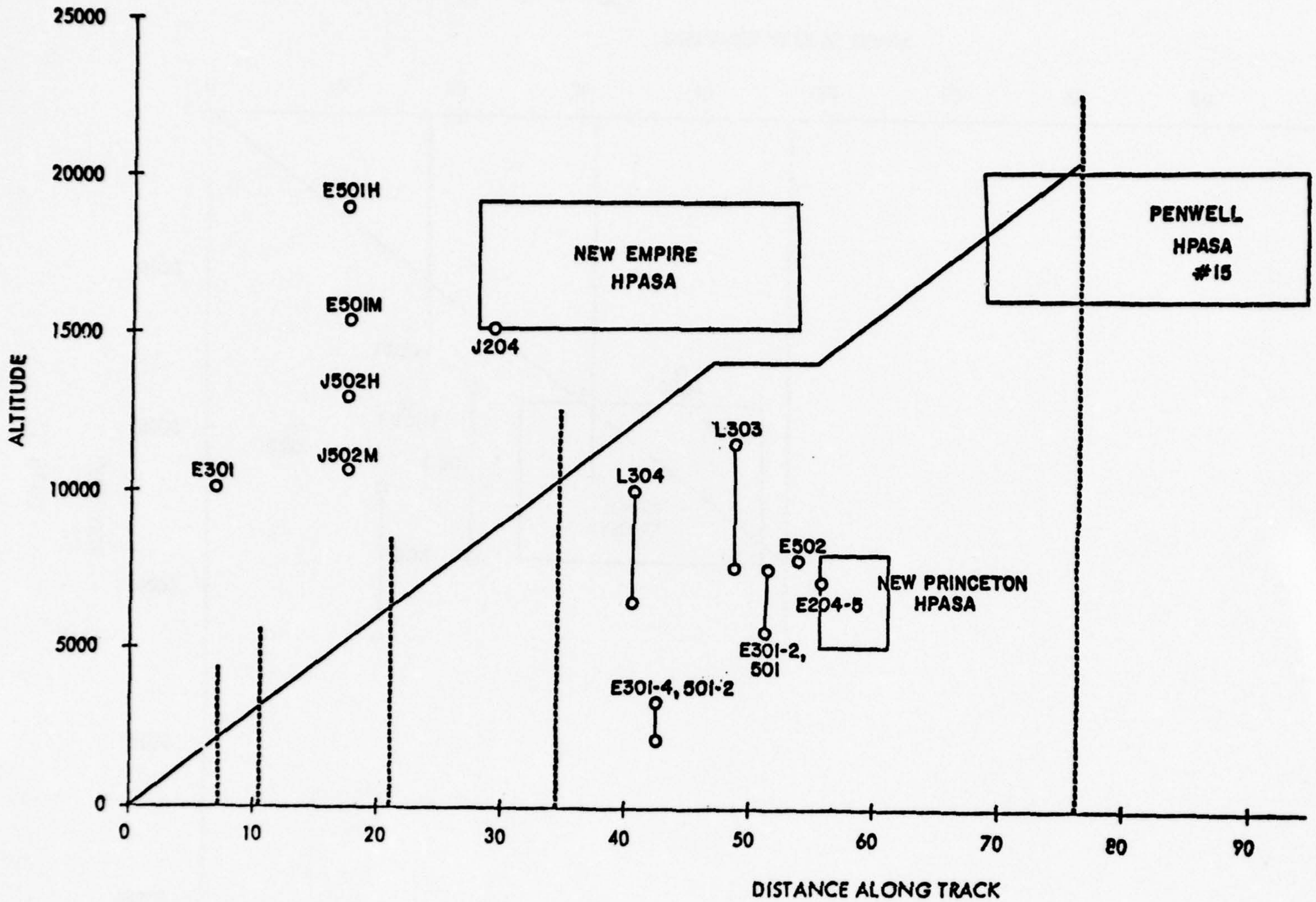


Figure D.15 Route L202

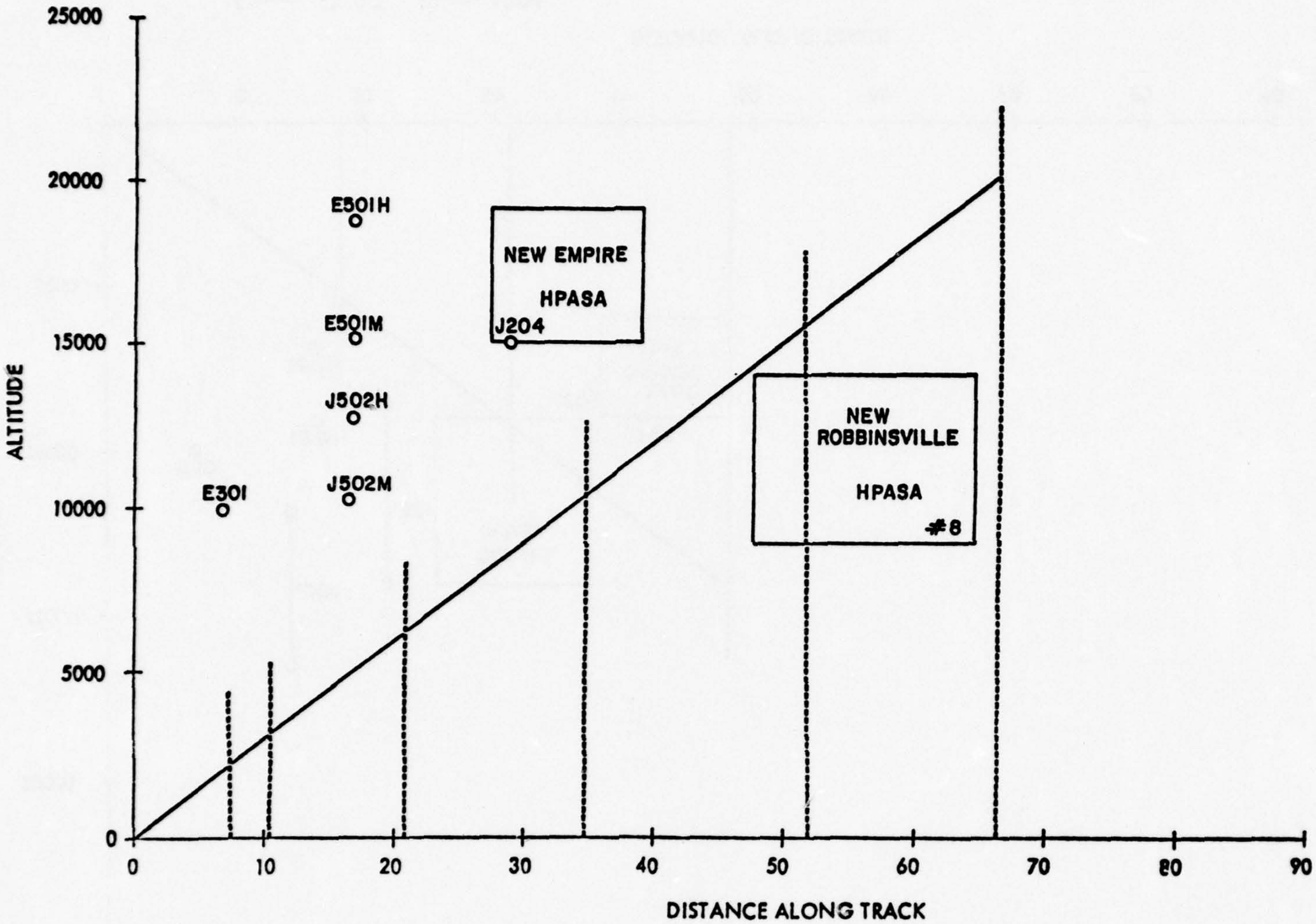


Figure D.16 Route L203

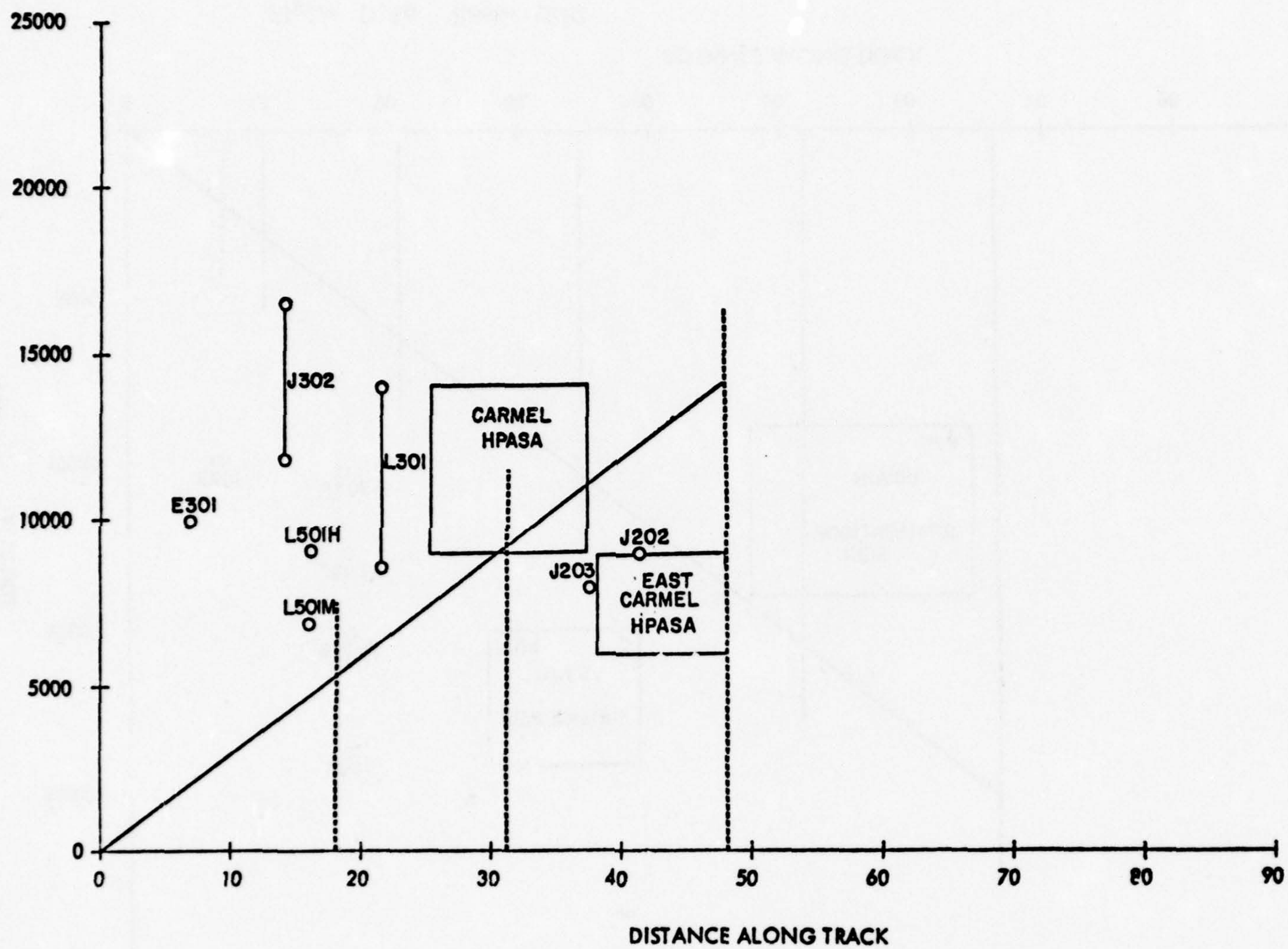


Figure D.17 Route L204

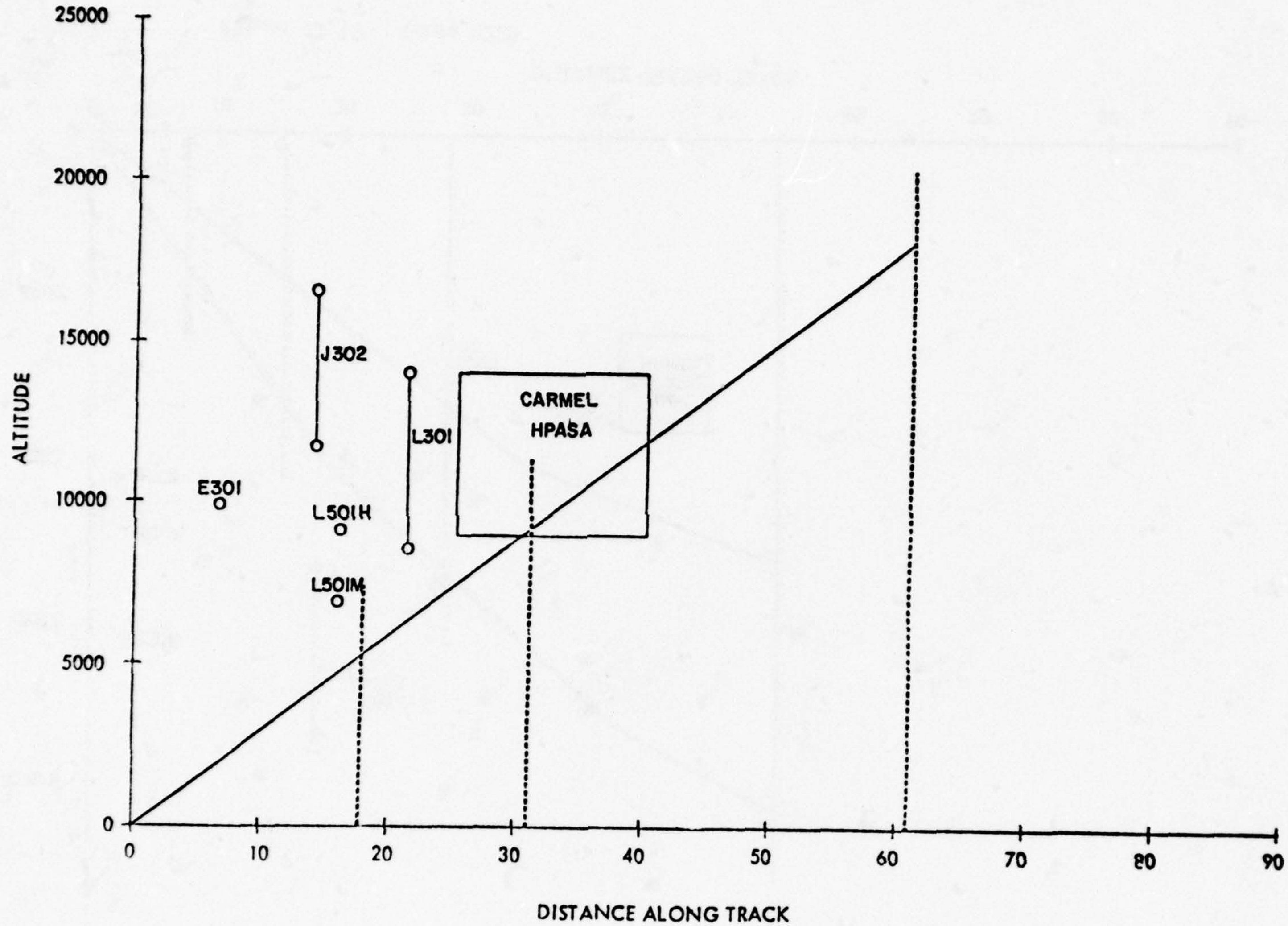


Figure D.18 Route 1205

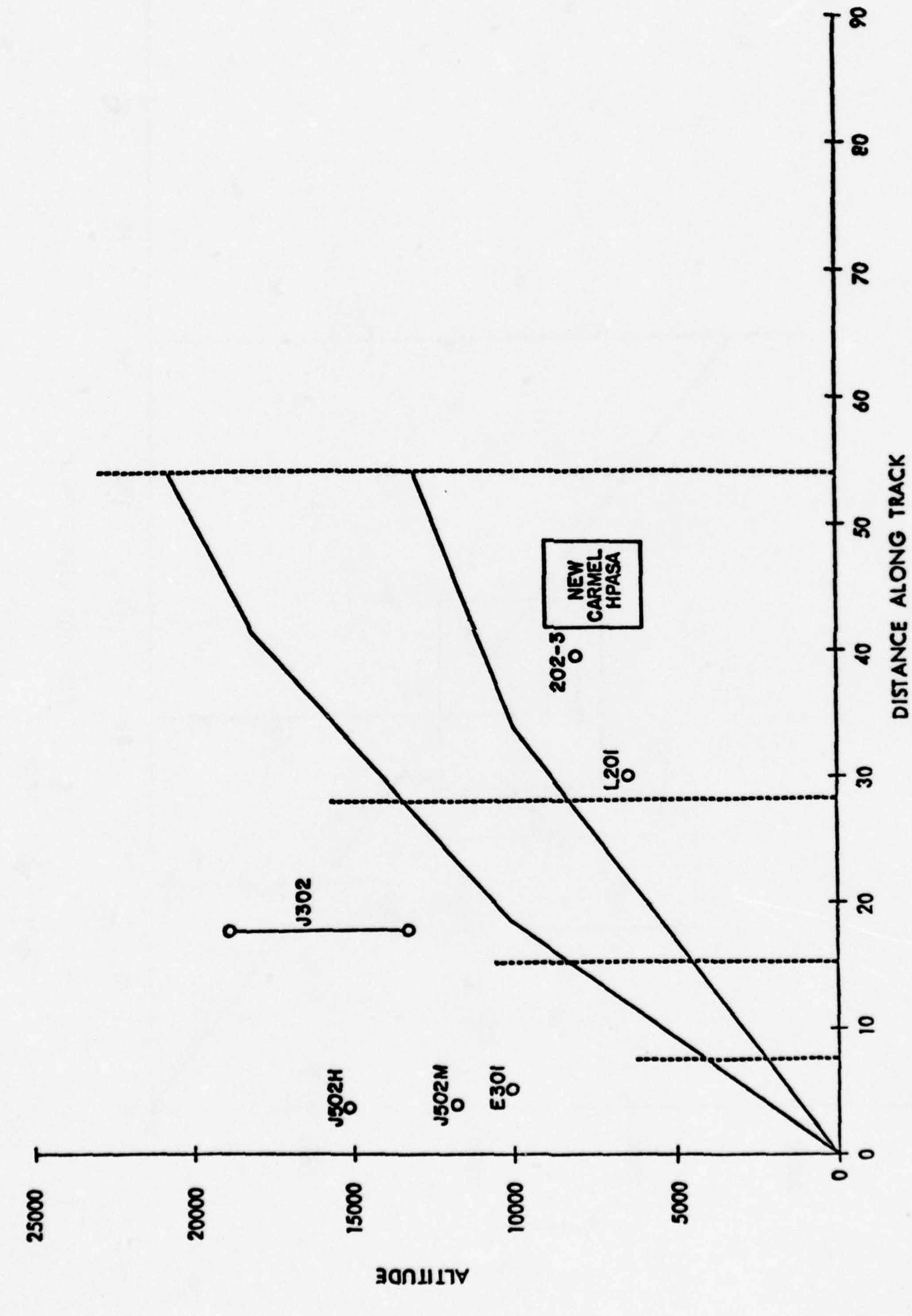


Figure D.19 Route L301

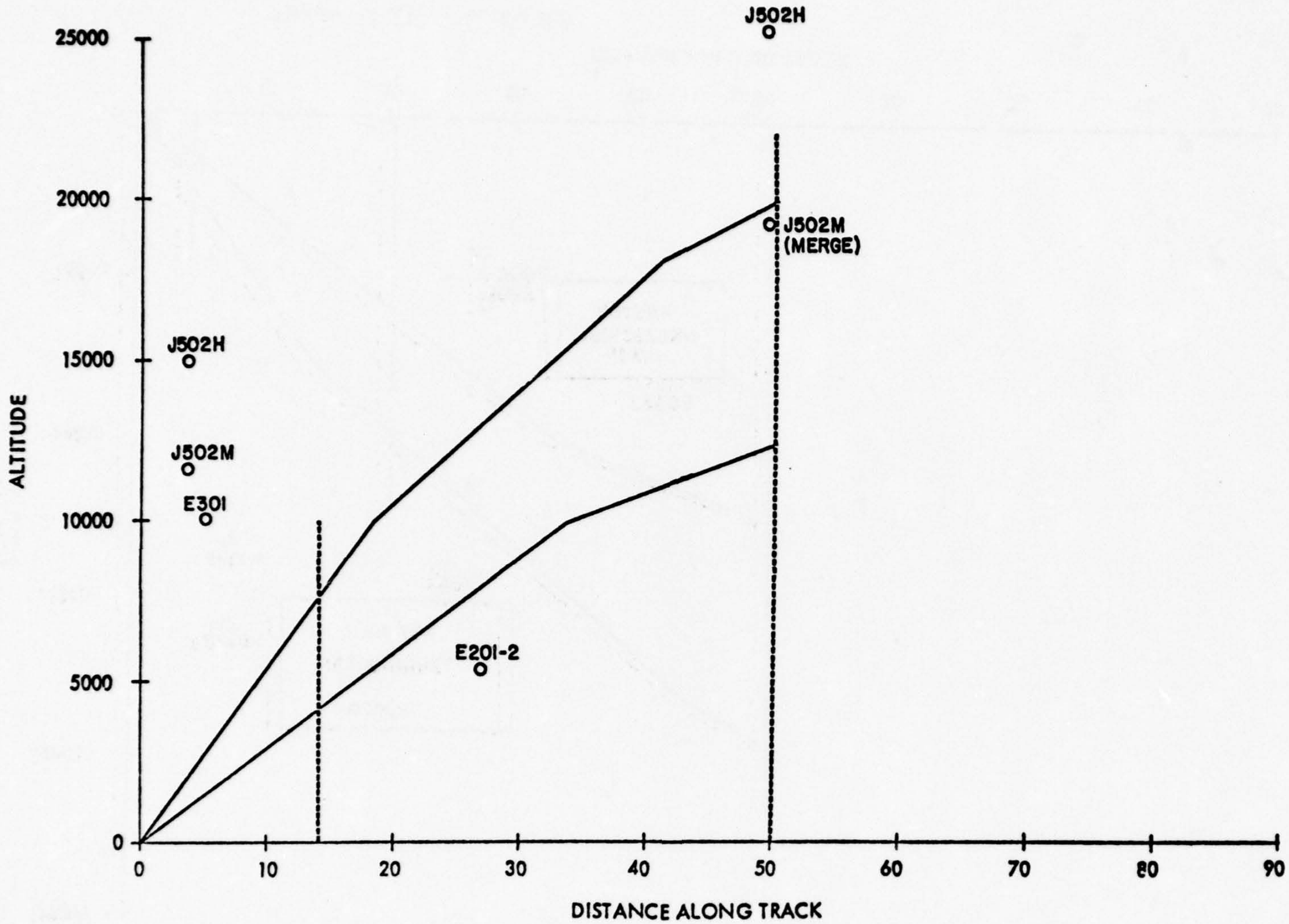


Figure D.20 Route L302

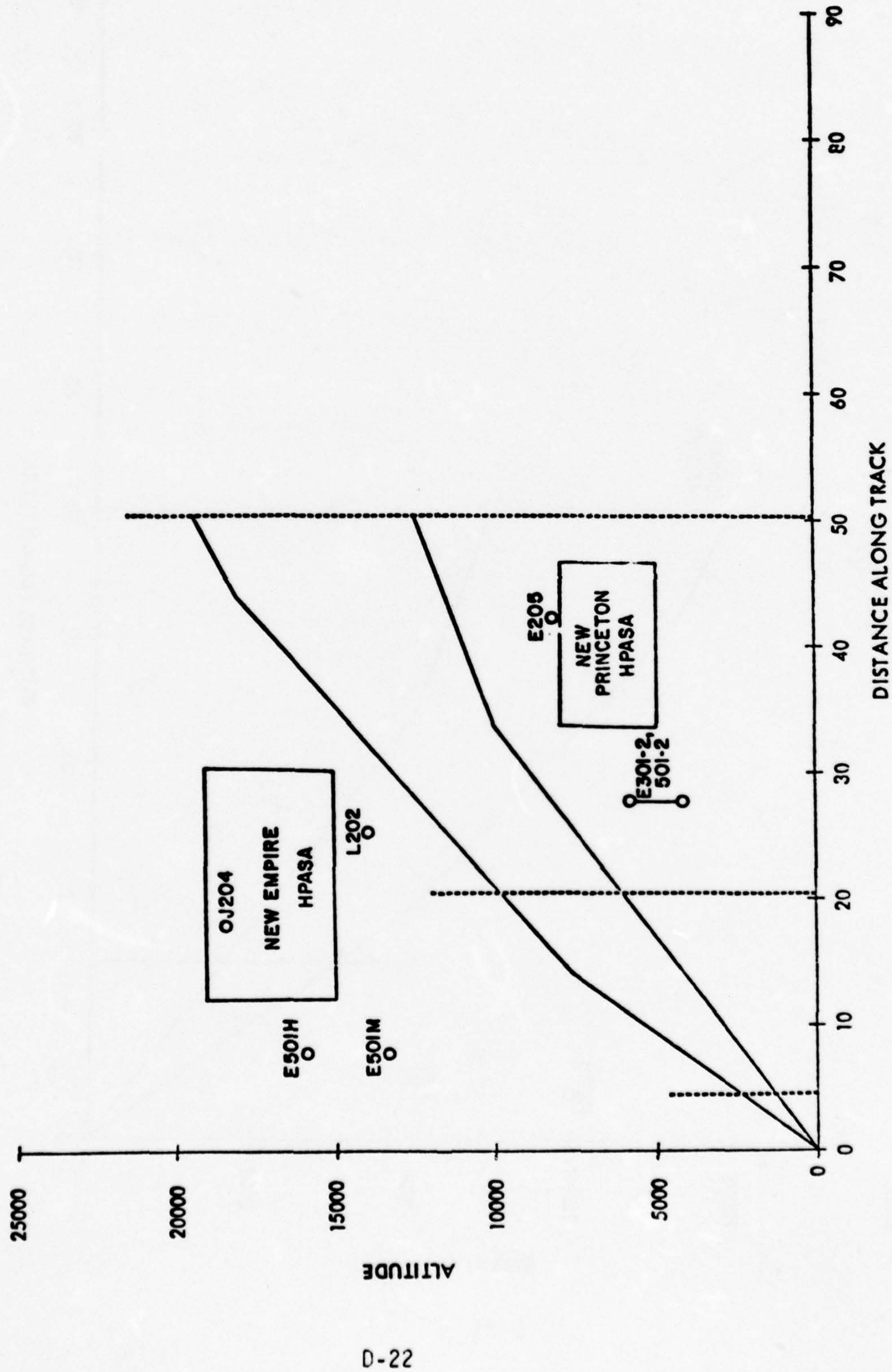


Figure D.21 Route 1303

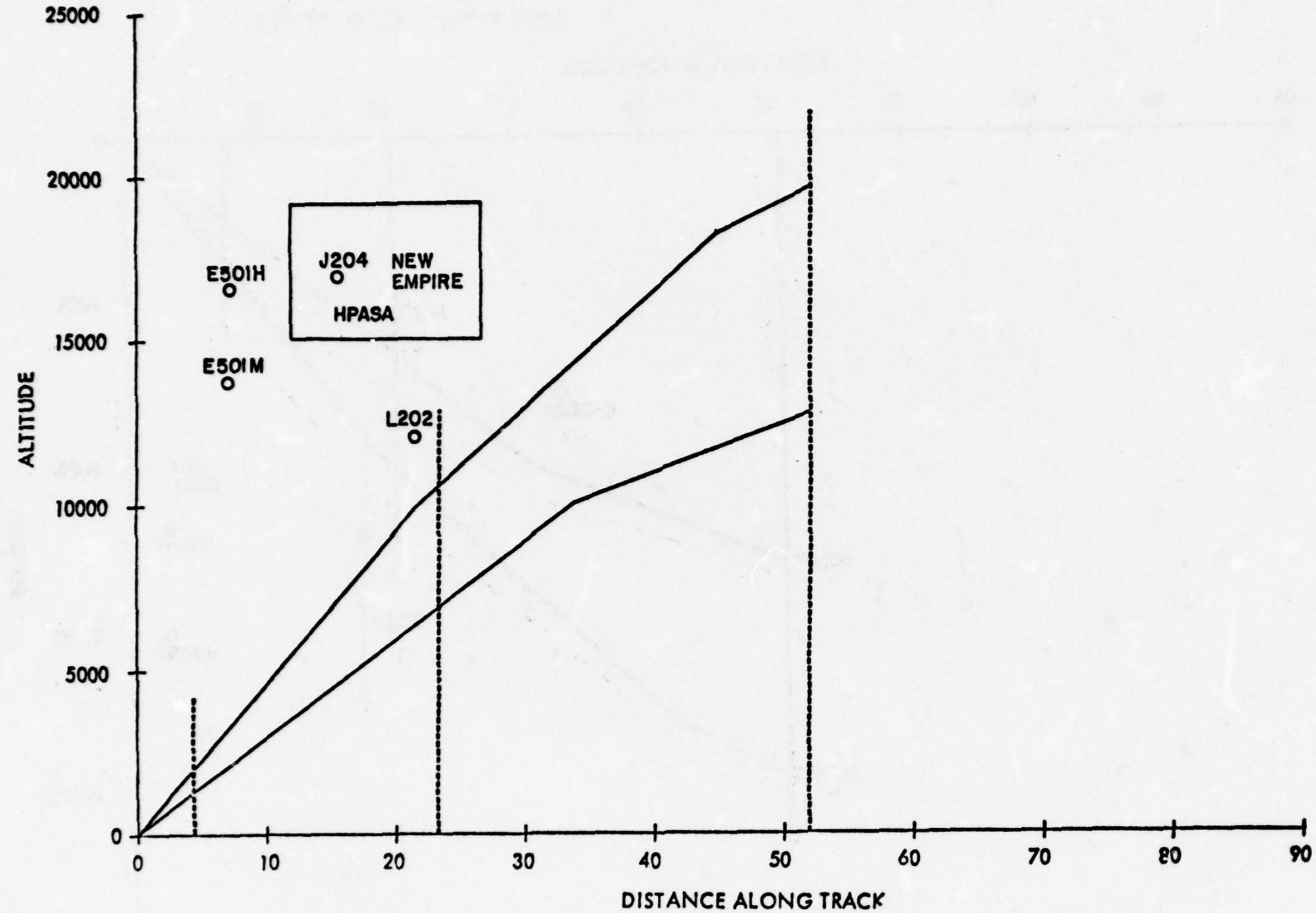


Figure D.22 Route L304

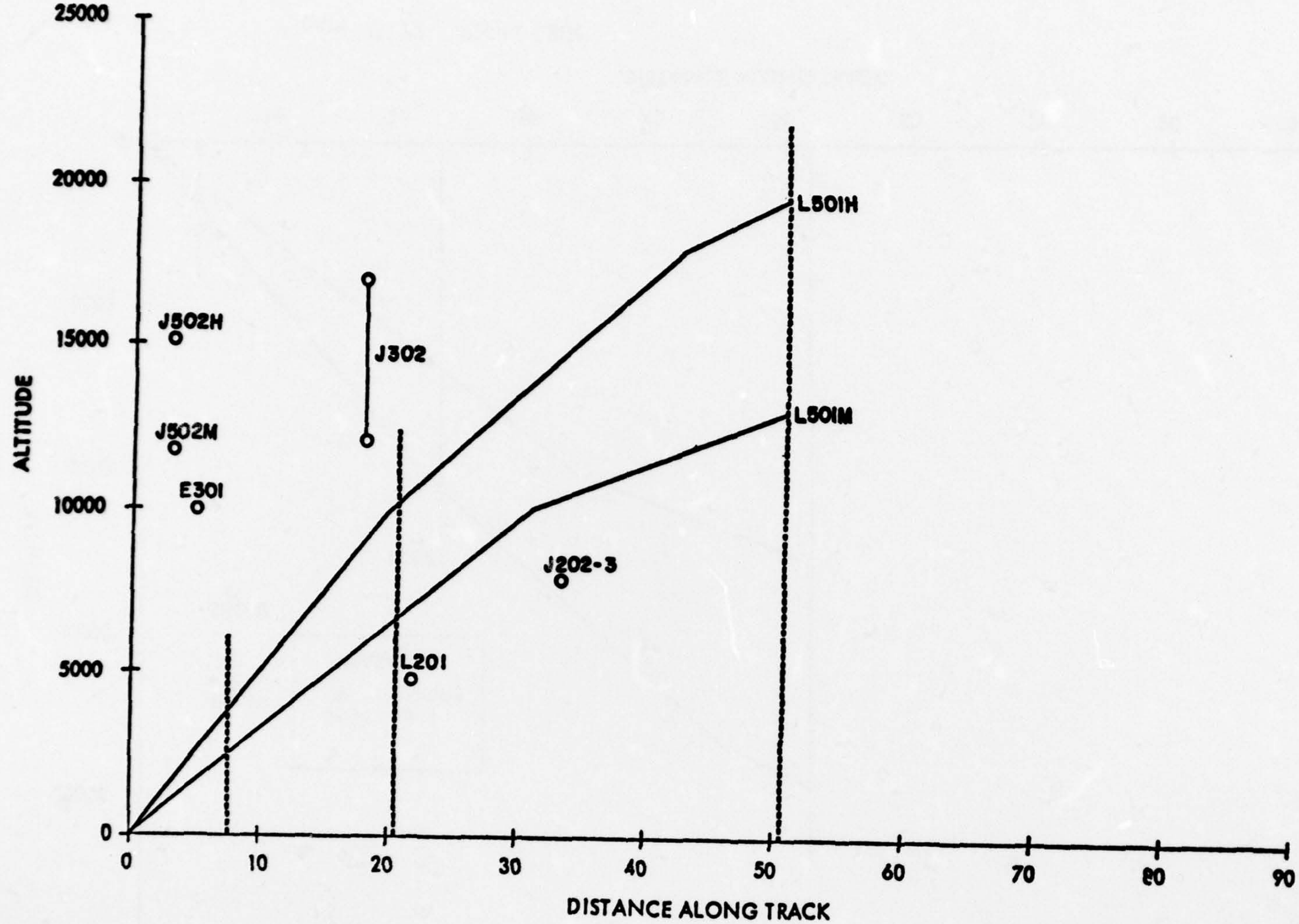


Figure D.23 Route L501

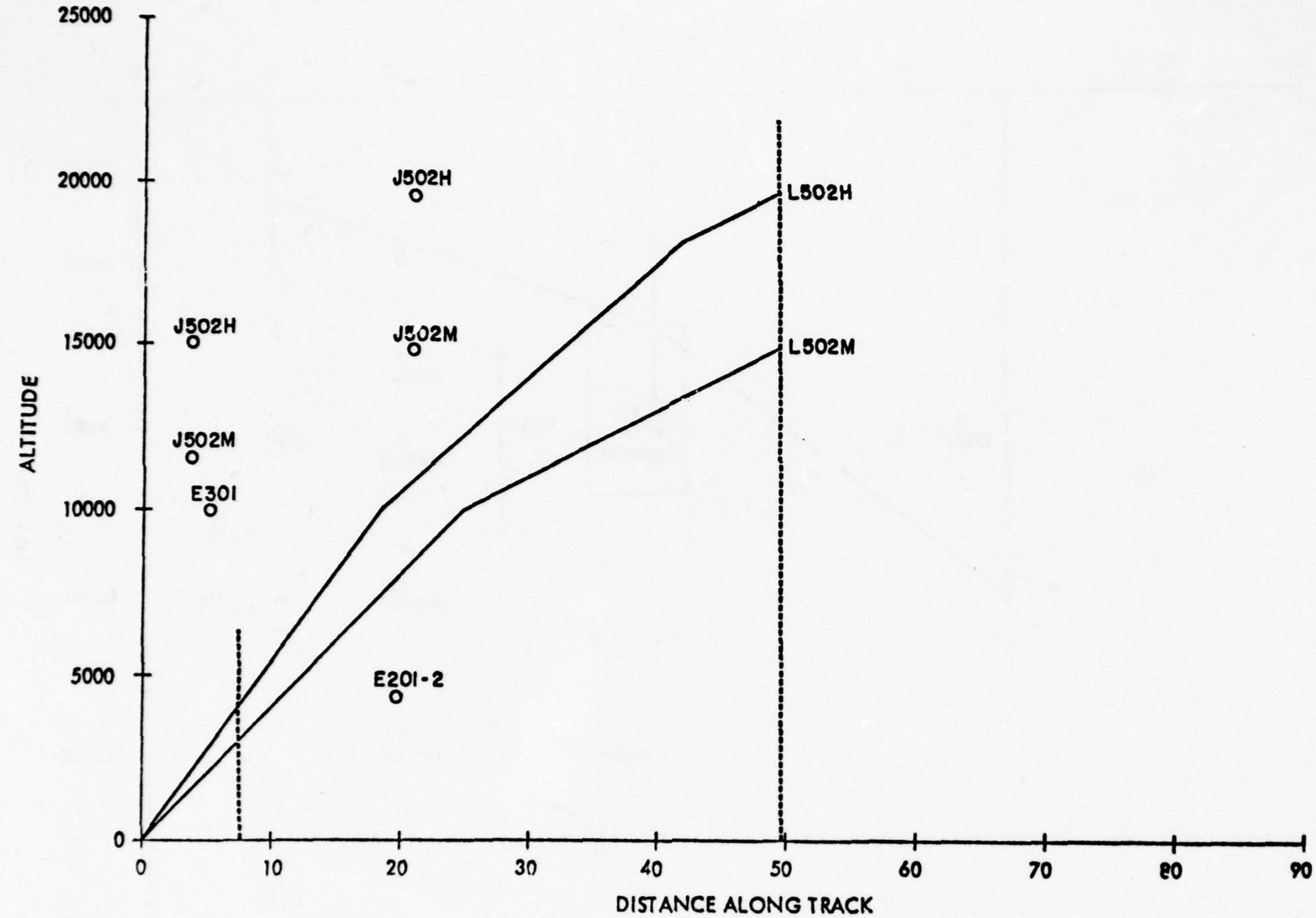


Figure D.24 Route L502

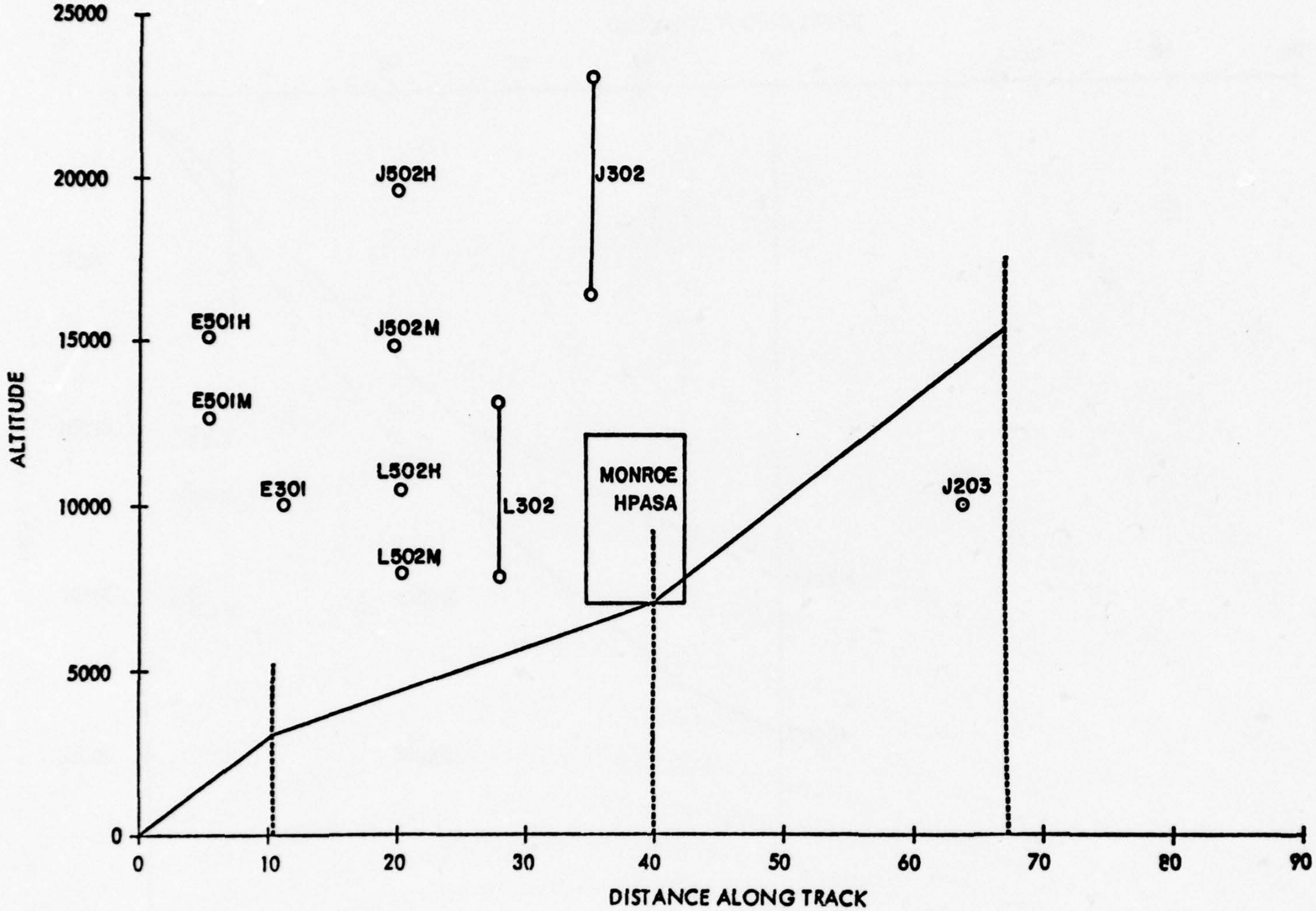


Figure D.25 Route E201

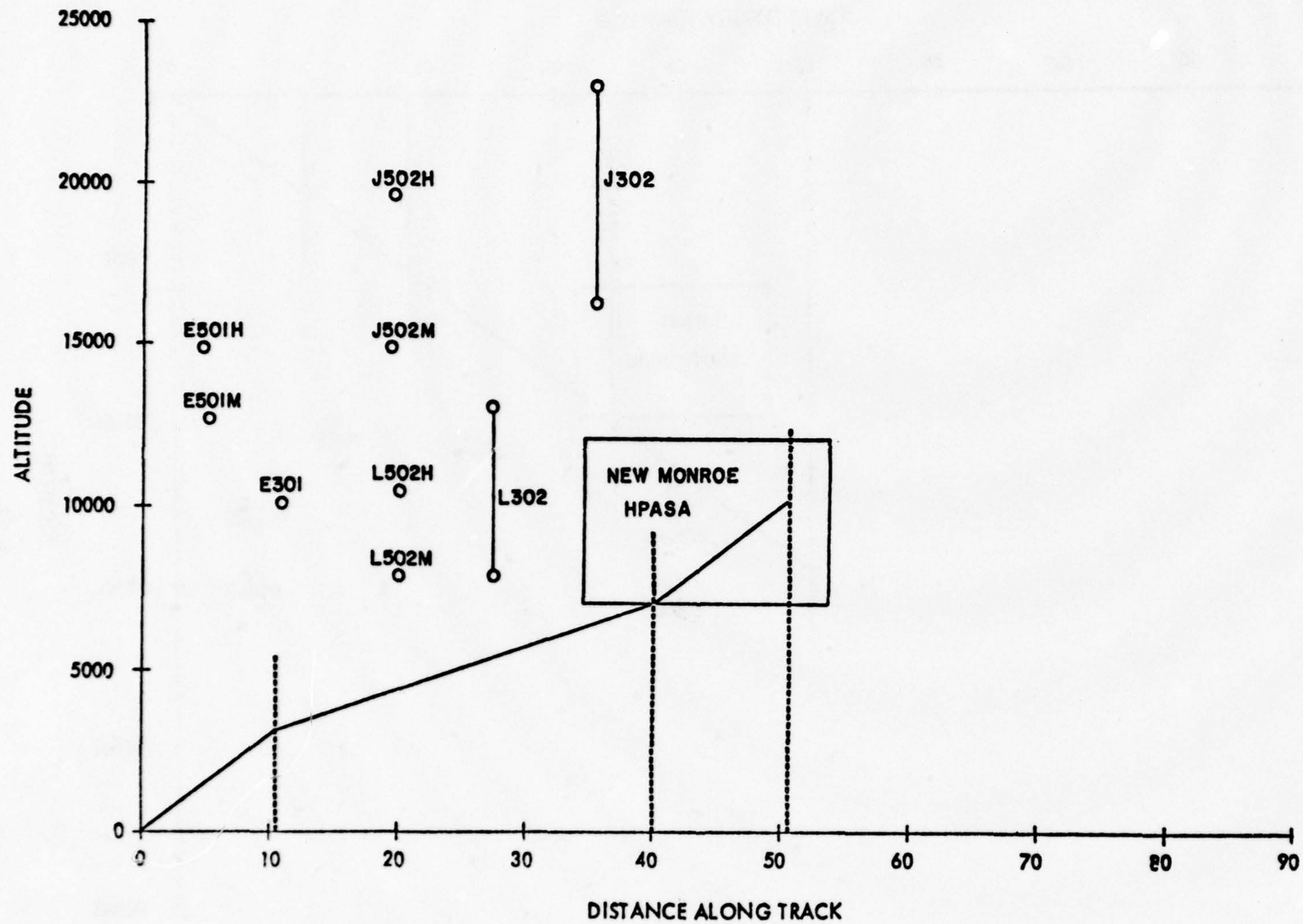


Figure D.26 Route E202

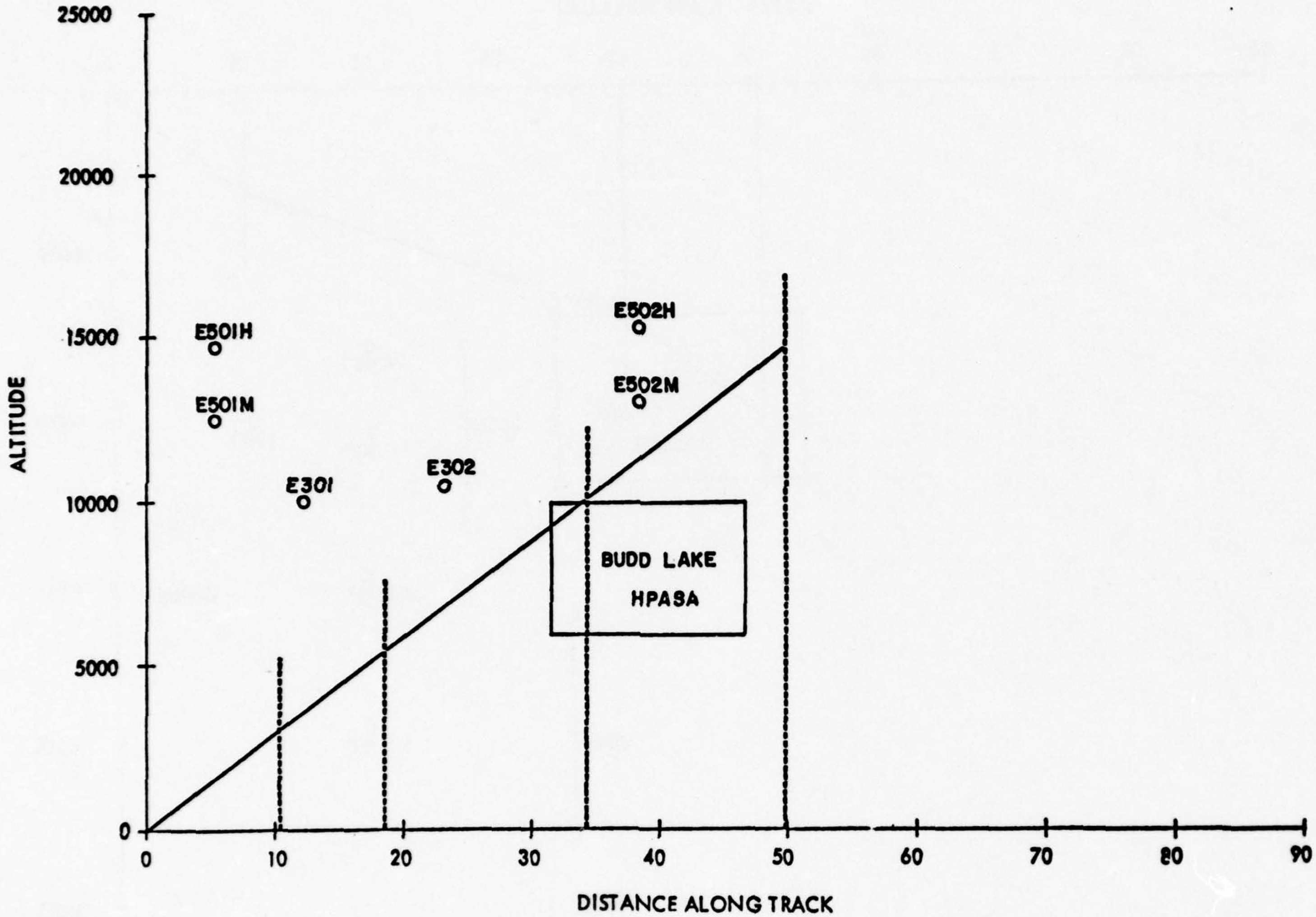


Figure D.27 Route E203

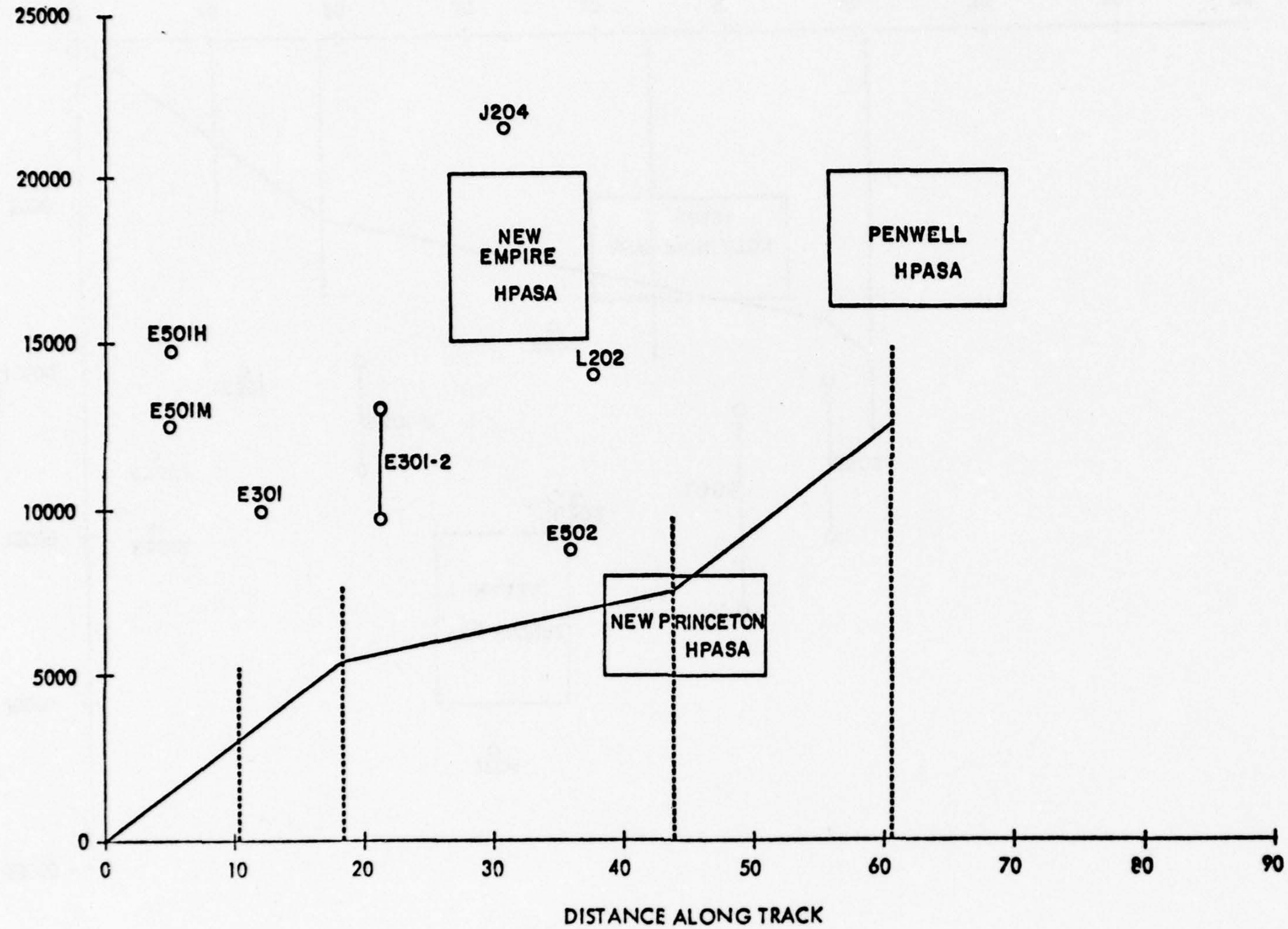


Figure D.28 Route E204

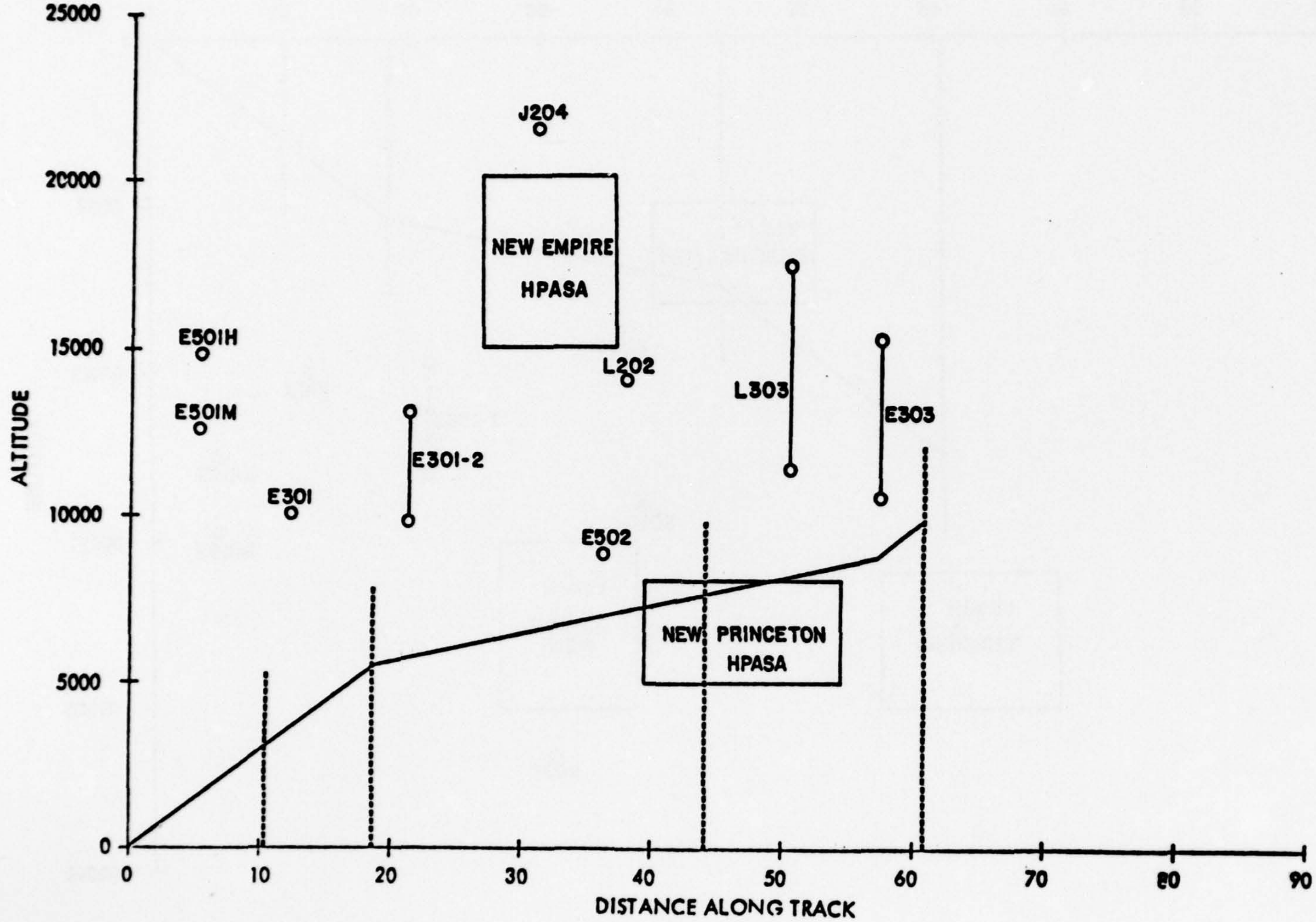


Figure D.29 Route E205

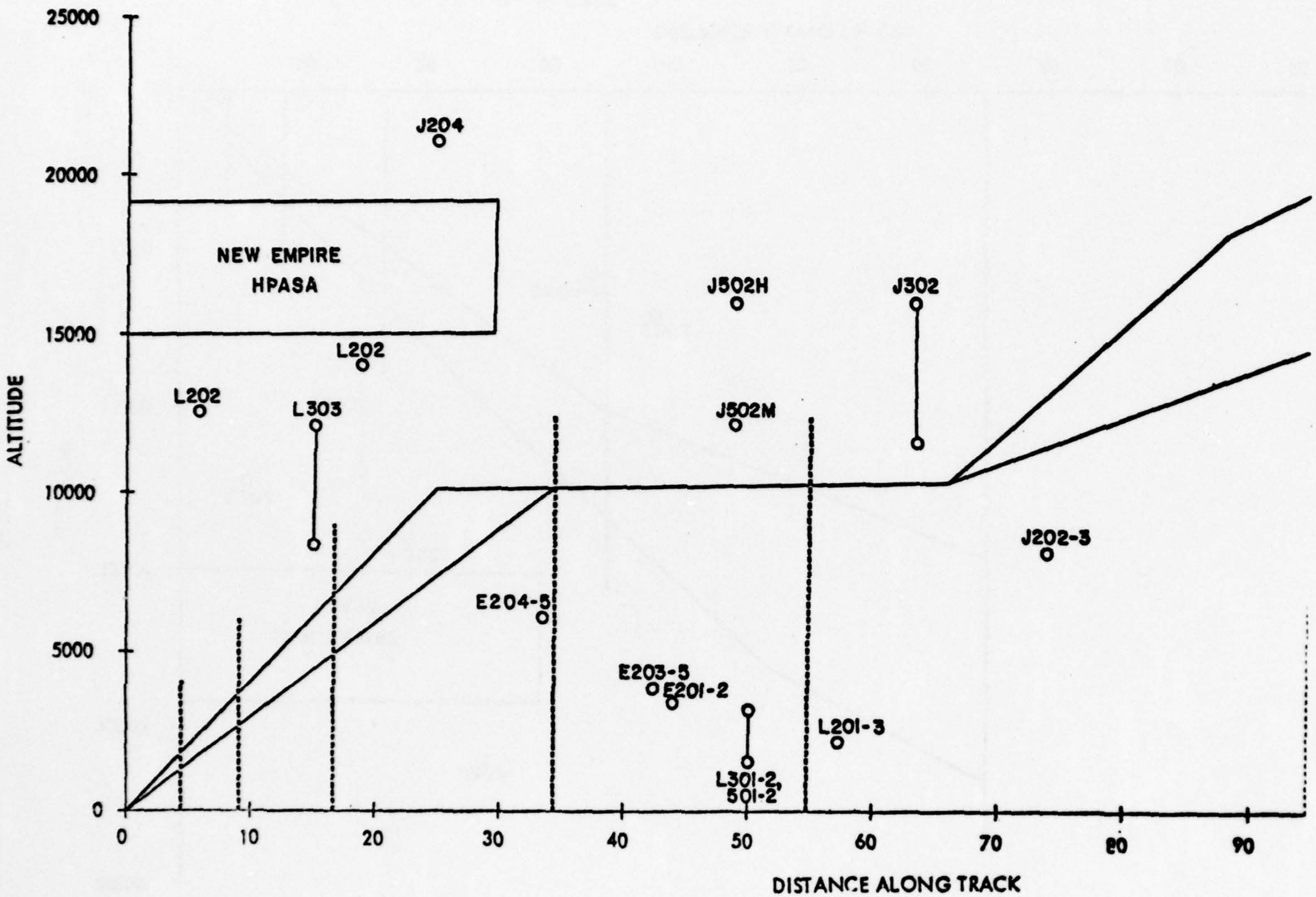


Figure D.30 Route E301

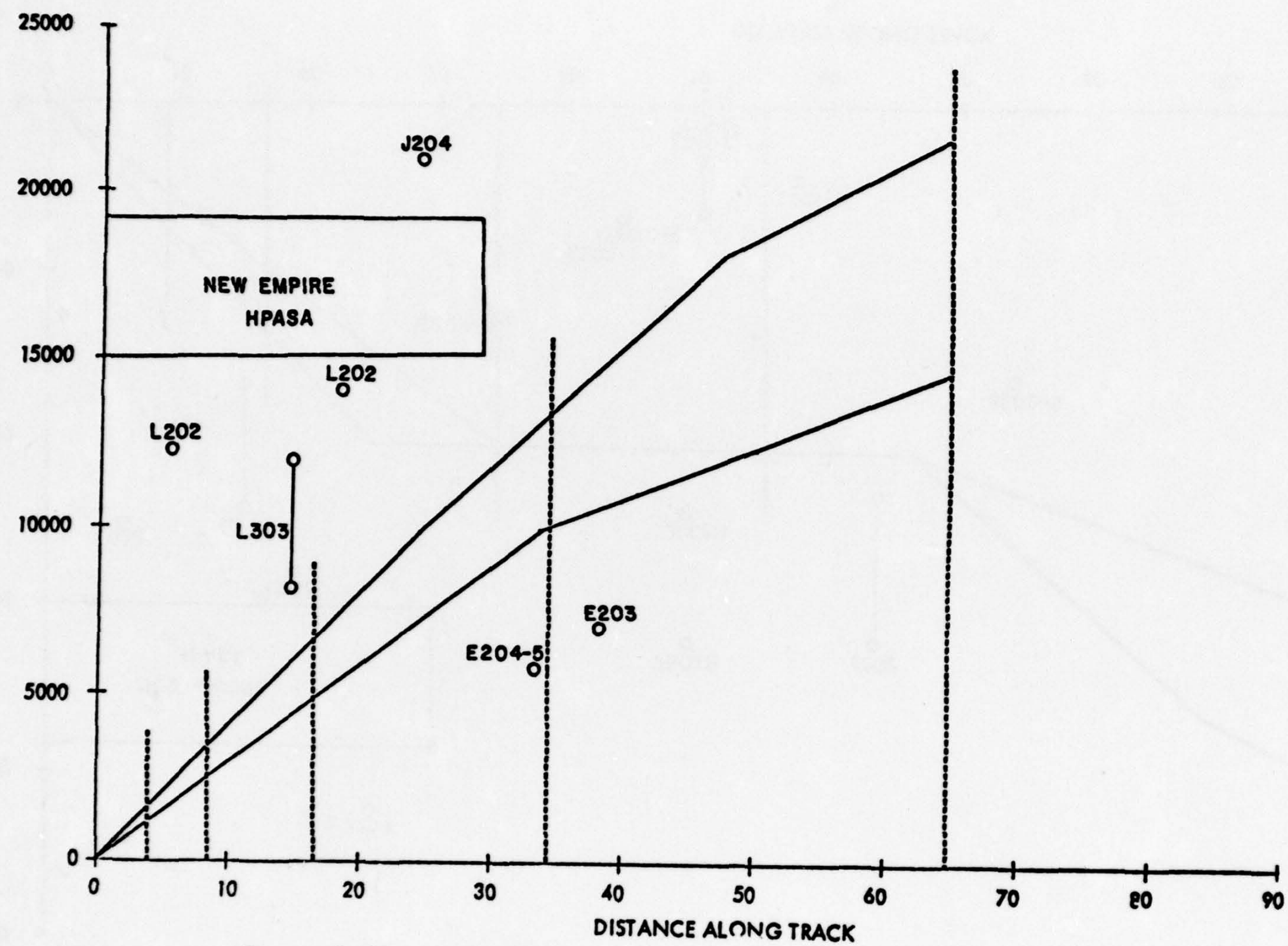


Figure D.31 Route E302

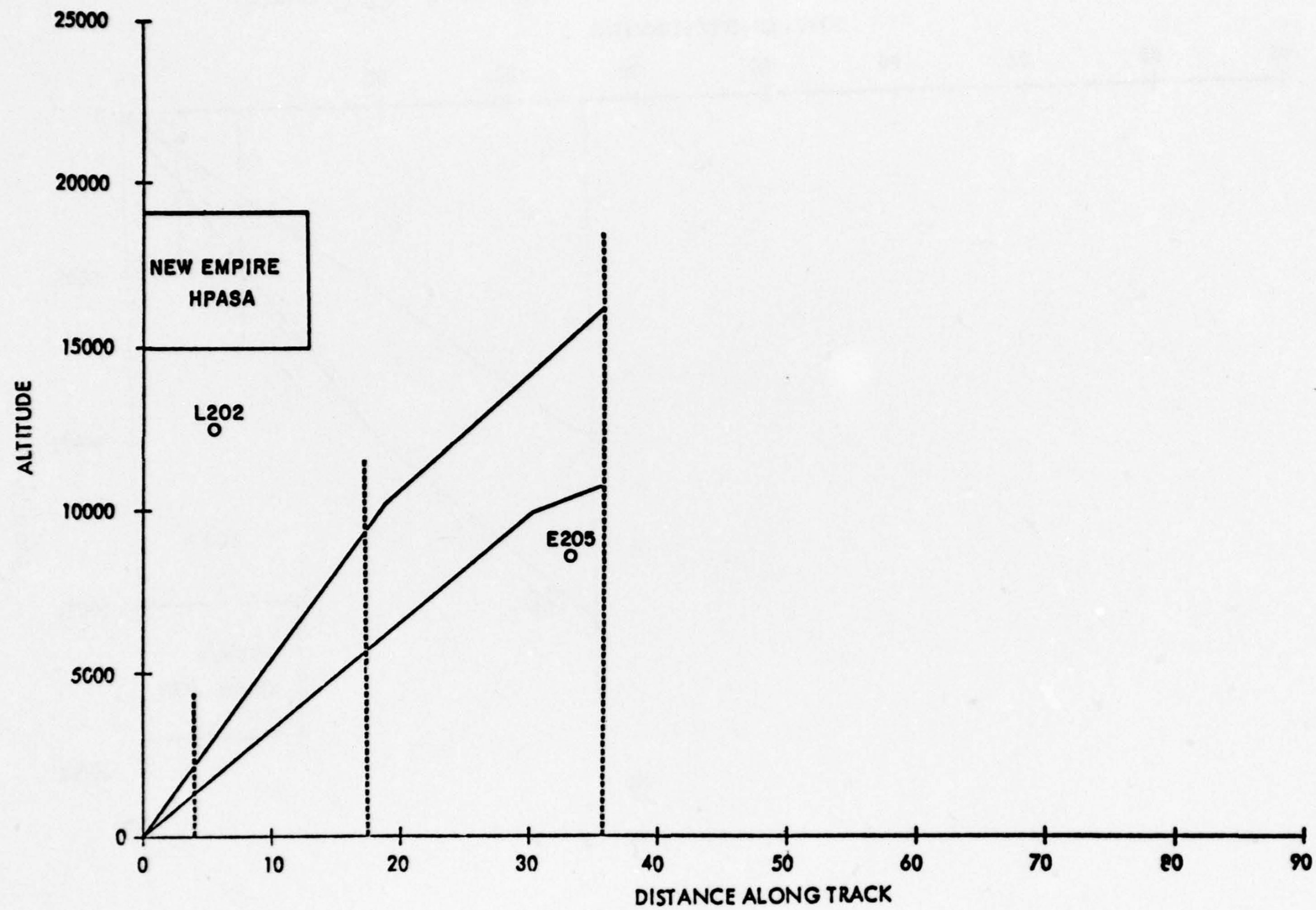


Figure D.32 Route E303

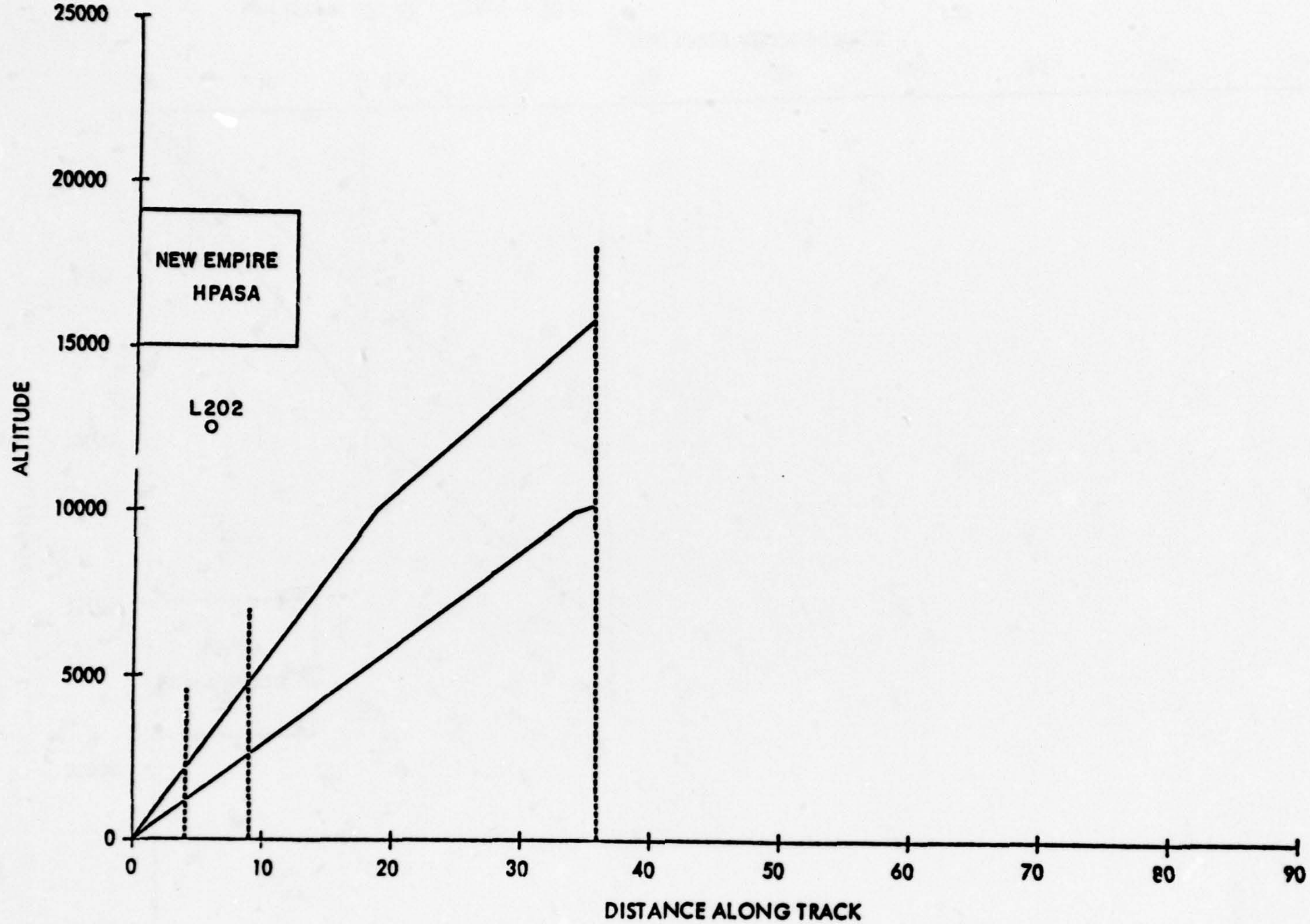


Figure D.33 Route E304

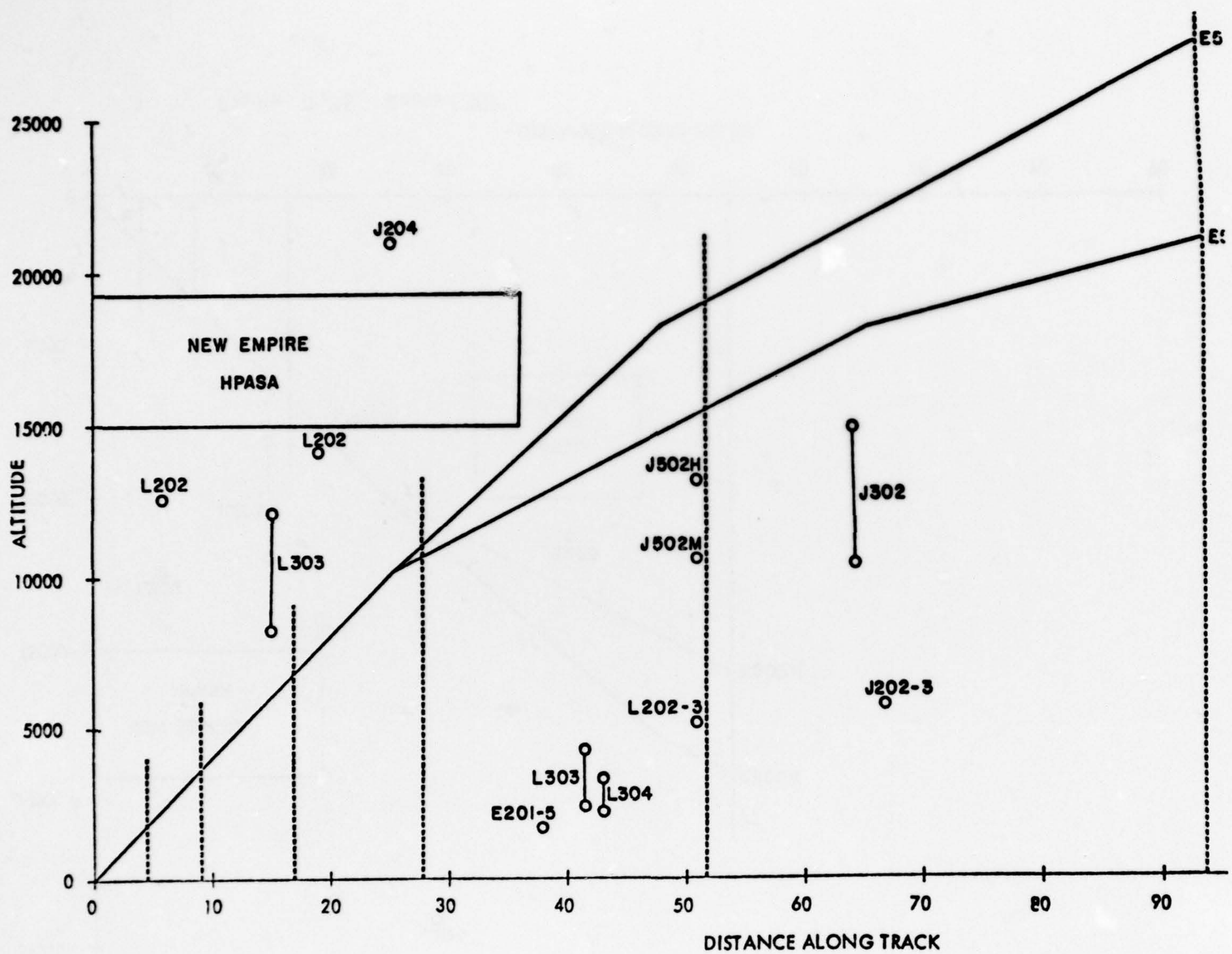


Figure D.34 Route E501

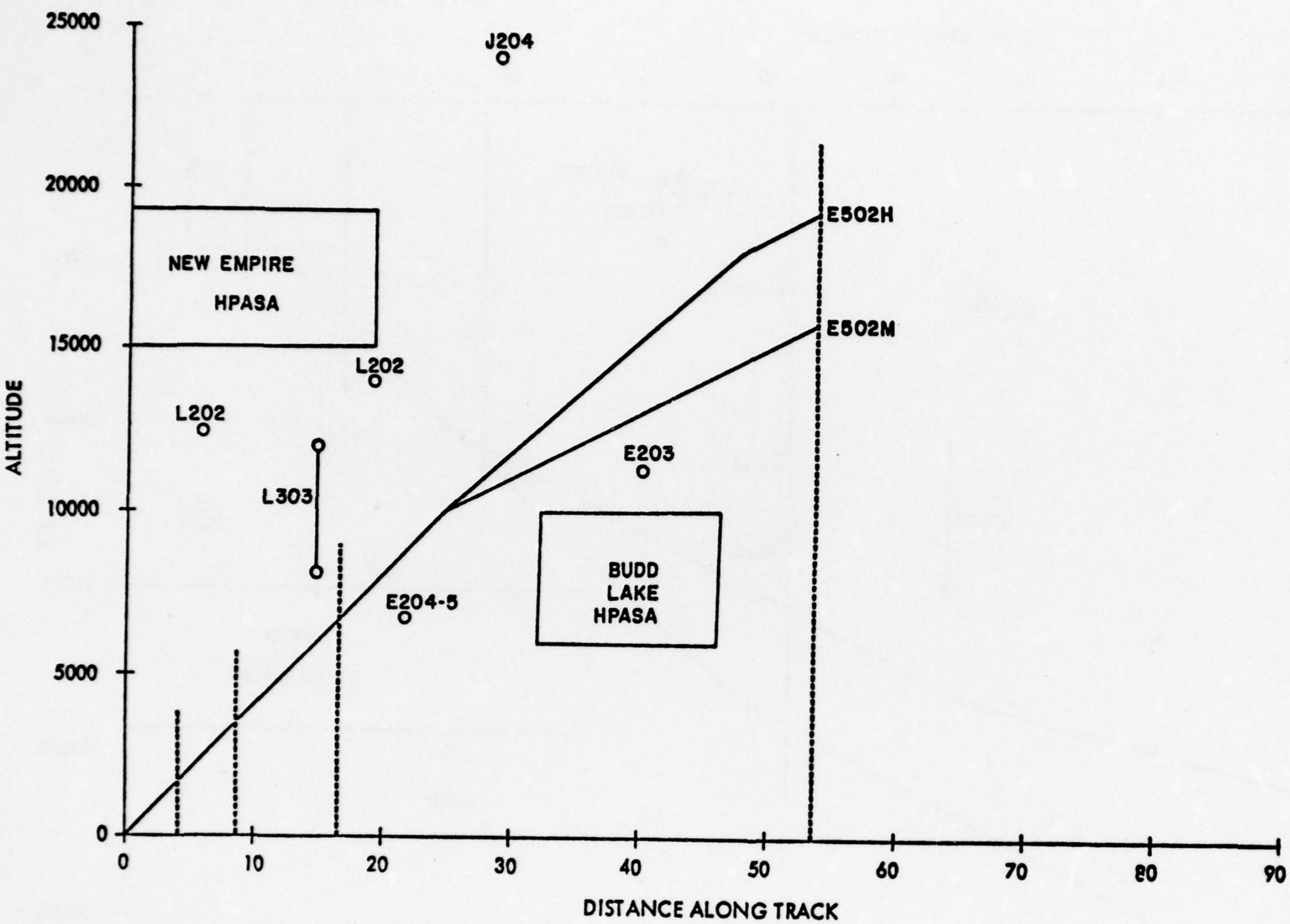


Figure D.35 Route E502

APPENDIX E

FIELD CONTROLLER APPRAISAL OF THE USE OF RNAV/VNAV IN TERMINAL AREA ATC OPERATIONS

E.1 INTRODUCTION

Considerable interest has been expressed by various groups in the involvement of journeymen air traffic controllers, drawn from field facilities, in this simulation in which RNAV/VNAV operations are introduced into a high density terminal ATC environment. The purpose of the introduction of field controllers in the training, exploratory, and data collection phases of the simulation served four major purposes: (1) to draw upon our current field experience in the refinement of the environment/procedures to be simulated, (2) to solicit our comments and reactions to the use of RNAV/VNAV in terminal area operations, (3) to derive quantitative simulation results from data collection runs in which we participated as test subjects, and (4) to provide us with some degree of familiarity with RNAV/VNAV operations through simulations.

Through the cooperation of the Air Traffic Service, Washington, D.C., and the regions and facilities represented, we were detailed to NAFEC to participate in the simulation. While NAFEC pool controllers also participated in the simulation, due to the high degree of interest expressed in our participation, the following appraisal represents our opinions only. The presentation of our appraisal, independent of any comments or opinion expressed by the NAFEC pool controllers, is provided to be responsive to this interest and does not imply any prejudicial judgment between the value to NAFEC pool controllers and our opinions.

E.2 BACKGROUND

We started the training phase in the operational use of RNAV/VNAV at NAFEC on June 16, 1975. The purpose of the training phase was to familiarize the digital simulation facility (DSF) target generator operators (DSF pilots), general aviation trainer (GAT) pilots, and the air traffic controllers with all required aspects of the simulation including geography, equipment and procedures. The training phase was scheduled to be followed by an exploratory phase during which the initial procedures, geography, etc. could be modified and refined prior to the data collection phase which was scheduled to start no later than August 4. Due to the numerous problems in the shakedown of the simulation equipment, the planned training and exploratory phase were frequently disrupted by various simulation system performance problems and failures and data collection was delayed until August 18, 1975. The need for extensive shakedown runs impacted severely on controller training and the exploratory phases of the simulation. The failure of the DSF targets to react in a predictable manner to ATC clearances (due to problems in the DSF not associated with "real world" RNAV/VNAV performance) worked to the detriment of an early understanding and efficient use of RNAV/VNAV functions in the control of air traffic. There may be a residual effect of this uncertainty as to compliance with ATC clearances and anomalous performance of the simulated targets which will impact

the objective results from the data runs. However, the opinions upon which the following apprasisal is based were formed prior to the completion of the data collection period and are expressions of our subjective analysis of the operational application of RNAV/VNAV to terminal air traffic control.

E.3 TERMINAL AREA RNAV ROUTE STRUCTURE DESIGN (2D)

It is our opinion that the RNAV (2D) structure design originally planned for simulation required some modification to provide a higher degree of flexibility for the controller, if such modifications did not adversely impact route miles, altitude restrictions, etc. to an undue extent on the system user. A modified design was developed which appeared to satisfy this requirement. The major difference between this design, which was developed during the exploratory period for use in data collection runs, and the original design was in the area immediately to the east of JFK. The original design located the departure routes serving departures to the northwest, north and northeast parallel to, and inside the downwind leg. The new design, which is discussed in more detail in the NAFEC simulation report, placed the departure routes outside the downwind leg. This change appeared to have no adverse impact on the system user. The modification was made based on the following operational consideration:

> There was a need for radar vectoring airspace, so that we could compare a 100 percent radar vectored operation with a 100 percent RNAV/VNAV operation. We would have been unable to compare these operations if we had to vector aircraft along the RNAV track.
>
> The original design was made by Champlain Technology Industries, and there were no provisions made for radar vectored aircraft in their design.
>
> The arrival route was moved inside the departures to give us more flexibility. We wanted to have the ability to shortcut traffic to runway 22L, from the downwind leg. This gave the final controller a true dump zone.
>
> The new design had more waypoints. Two of the new waypoints were positioned closer to the outer marker. This enabled the final controller to switch any arrival to either runway by the use of RNAV.

E.4 TERMINAL AREA VNAV ROUTE STRUCTURE DESIGN (3D)

The original design planned for simulation allowed for the use of "stacked routes" for arrival/departure traffic. (The term "stacked routes" is used here to describe two or more routes having common or near common horizontal paths which are separated vertically based on VNAV (3D) separation criteria.) It was envisioned that a unique application of VNAV arrival routes would result through the use of two-segment approaches which were to be included in certain parts of the simulation tests. However, when it was learned that the FAA did not support the use of two-segment approaches, this application was no longer considered viable. Therefore a renewed and major emphasis was placed on determination of other potential uses for VNAV and its unique capabilities

as they might relate to both terminal airspace design and ATC operational use of VNAV as a control tool.

In order to clarify the unique use of VNAV in combination with the two-segment approach concept, and why this combination appeared to offer some potential advantage in the use of stacked routes, the following illustration (Figure E.1) is provided. As shown, using a two-segment approach to runway 22R and a single-segment approach to runway 22L, traffic from the east could fly stacked routes with the aircraft on the higher route intercepting the localizer for runway 22R at a higher altitude and executing a two-segment approach. The aircraft on the lower stacked routes would intercept the localizer for runway 22L at a lower altitude and vertical separation could be provided between the two aircraft until both were established on their respective localizers. Since two-segment approaches were dropped from the simulation tests it is not known whether this combination would provide any operational advantage or not. However, two-segment approaches, when used as illustrated, did appear to provide a means for "unstacking" stacked routes.

Our efforts to develop discrete VNAV routes was not limited to stacked routes but was an extension of the previous work done by Champlain Technology Industries. In their terminal route design activities and other analyses by SRDS and NAFEC prior to and during simulation planning. While the capabilities of VNAV were recognized by us as potentially beneficial to the ATC system user, it was the consensus that the only unique, potentially advantageous, property of VNAV related to terminal airspace is the capability to define the vertical dimension of a path through space as though the path were described with an infinite number of altitude checkpoints.

A number of applications of VNAV to route structure design were considered. During these studies we were advised not to consider either the original or modified route structures as a constraint to the development of routes discrete to VNAV operations. We were in effect given complete freedom to invent any route that potentially would exploit the use of VNAV. The effort was aimed at defining a route or series of routes that, by their nature, could be used exclusively by VNAV equipped flights rather than routes that could be used by both RNAV and VNAV equipped traffic. This approach was taken to identify any airspace design application based on the unique capabilities of VNAV.

As a result of this effort, no VNAV-only charted route structure or individual routes were developed. It was our opinion that no need or advantage could be found in airspace design for discrete VNAV-only routes. It was concluded that a good terminal route structure would accommodate both RNAV and VNAV traffic.

E.5 RNAV ATC APPLICATION

The following represents our opinions as to the advantages, disadvantages and limitations to the use of RNAV in terminal ATC operations. These opinions presuppose that certain conditions relative to avionics equipment and pilot performance are met.

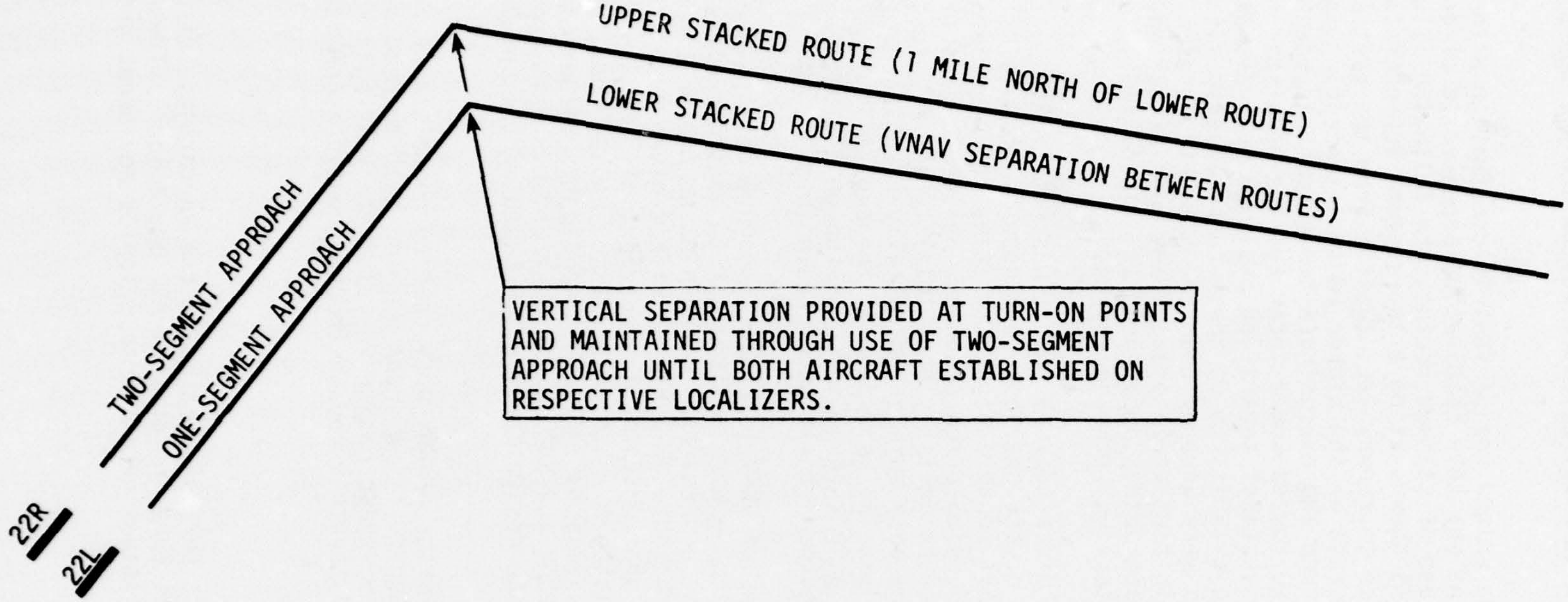


FIGURE E.1 EXAMPLE OF STACKED ROUTE/TWO-SEGMENT APPROACH APPLICATION

Conditions - (1) RNAV turn anticipation (both automatic and manual) will be performed in such a manner that the approximate ground track can be anticipated by the controller. This assumes that both automatic and manual turn anticipation procedures be standarized to minimize the requirement for radar vectoring to compensate for turns that deviate from the expected ground path.

(2) All RNAV flights will be capable of flying at least a ten-mile parallel offset.

(3) All turns to and from offsets will be accomplished using a common departure angle from the parent/offset route unless otherwise specified by the controller.

(4) All RNAV equipment will permit assignment of "direct to" waypoint clearances and compliance with such instructions will result in the aircraft flying a direct path to the assigned waypoint upon completion of any required turn.

(5) Offsets may be cancelled prior to the time the aircraft achieves the assigned parallel offset distance form the parent track.

(6) Flights on a "direct to" clearance can be assigned an offset parallel to the direct flight path.

(7) All RNAV functions simulated will be available.

(8) Charted SID's and STAR's with altitude restrictions are published and that such SID's and STAR's are so designed as to provide flexibility for spacing and sequencing of traffic equivalent to that required in a radar vector operational environment.

While condition (6) was not met by the DSF targets, condition (6) is believed to be realistic and available in some, if not all RNAV systems, and our appraisal of the use of RNAV in terminal operations assumes that all of the preceding conditions would be met. This appraisal, based on both experience in the NAFEC simulation and in current field facility terminal air traffic control, is organized by specific areas of potential ATC impact and summarized in a general appraisal statement.

Controller Radio Communications - We feel that there would be some reduction in radio communications for the feeder controllers in a 100 percent RNAV/VNAV operation.

There would be a greater reduction of radio communications in a 100 percent RNAV/VNAV departure operation. However, there was minor reduction on the final control positions.

The reason for the reduced communications is that each SID departure or STAR arrival has a predetermined route to fly with all the altitude restrictions on it. The controller need only monitor the flight and make occasional RNAV maneuvers to accommodate overtaking or merging traffic situations.

The Role of RNAV Maneuvers vs. Phase of Flight - RNAV Limitations: Because of differences in navigational error and turn anticipation, separation standards in critical areas such as base leg or turns to final, can, and often do, diminish separation to less than prescribed minimums. Whereas radar vectors, being more precise when employed properly, can be benefically substituted in these same areas to provide more exact required separation.

Impact of Mixes of RNAV/Non-RNAV Operations - Both the departure and feeder controllers found no appreciable differences between mixed traffic situations. It was just as easy to assign a heading off a fix or off the runway, as it was to issue an RNAV maneuver. However, the final controller's workload increases if he incorporates RNAV instructions for the RNAV aircraft and vectors to the non-RNAV aircraft.

Impact of Mixes of VNAV/RNAV Operations - No differences noted.

System Capacity - RNAV will not affect traffic capacity in the terminal area, in that it is possible to run a three-mile final with RNAV or with radar vectors. Present day standards require three-mile separation and this can be accomplished with or without RNAV.

General Appraisal Statement - It is our opinion that RNAV/VNAV procedures may well be applied in the terminal area to provide a safe, orderly and expeditious flow of air traffic. We feel that RNAV routes with altitude restrictions to which VNAV usage can be applied, as pilots may desire, should be established at as many busy terminal areas as may be deemed beneficial by FAA and user groups. We feel that these routes should initially co-exist with established airspace allocations to the maximum extent possible to insure little or no adverse impact on present day operations. We also feel strongly that radar vector procedures should be employed at the discretion of the controller in critical areas where RNAV/VNAV may not be as precise as radar. We believe that RNAV/VNAV will be beneficial to the user in that properly established routes can and will reduce flying miles and time. It will be beneficial to the user and more particularly to the controller under all traffic densities, in that the controller will normally have to provide fewer control instructions, subsequently allowing him to perform duties which may include handling more aircraft per sector, combining sectors or portions of sectors, and freeing him to provide both essential and additional services at a reasonable level.

It is felt that RNAV/VNAV could work well in a high density terminal area. RNAV STAR's should be made for the entire route of flight including the final approach. RNAV/VNAV could be used to set up straight-in approaches to satellite airports that have no navigational aids.

E.6 VNAV ATC APPLICATION

The following represents our opinions as to the advantages, disadvantages and limitations to the use of VNAV in terminal operations.

During the pre-data collection and data collection periods of the simulation, little or no operational use was made of the functions peculiar to

VNAV. While those functions common to both RNAV and VNAV were used to a major degree, there were no occasions found for the use of VNAV as a control tool. In addition, it was our opinion that while VNAV capabilities have the potential for providing advantages to the user in the manner in which climbs and descents can be accomplished, these potential advantages do not require the establishment of exclusively VNAV routes. Such advantages are available in a well structured RNAV terminal route system.

When VNAV vertical separation is being applied between aircraft on crossing courses, vertical separation criteria are predicated upon mathematical curves, which increase separation requirements proportionately with any change of the course angle convergence or divergence, and any increase of degree of vertical path angle. These VNAV separation standards can only increase the present day minimums which dictate one thousand feet vertical separation between IFR aircraft and which can more efficiently and effectively be applied through step-up or step-down procedures in use today. Also due to the complex nature of the mathematical curve, a controller could very rarely move an aircraft laterally from an established track and still insure separation from a crossing course. Impromptu courses would be out of the question, as altitude separation requirements could not possibly be computed by the controller.

When VNAV vertical separation is being applied between aircraft in a parallel climb or descent on the same lateral track, separation criteria in accordance with the Vertical Separation Requirements curves is increased over criteria which can be applied through the use of today's step-up or step-down procedures. If an aircraft is moved laterally from the main track, separation from another aircraft, which had previously been separated by the minimum criteria, either above or below, immediately ceases to exist due to the proportionate vertical separation increase caused by course angle divergence in the mathematical curve. Impromptu courses would again be out of the question, as controllers could not compute descent angles or altitude separation requirements.

VNAV could be used as a useful tool to pilots as a more economical means of climb or descent.

RNAV/VNAV could be used to set up straight-in approaches to satellite airports that have no navigational aids. It could also be used to set up an artifical glide path to aid in VOR approaches, which would possibly lower minimums.

The foregoing appraisal represents the expressed opinions of the following named field controllers who participated in the NAFEC RNAV/VNAV simulation and is based on our experience in the simulation and our judgments as current field facility air traffic control specialists.

[Signed]

D. B. CARLSON	Atlanta Tower
JULES M. ROSENTHAL	New York Common IFR Room
GERALD R. FROST, JR	Bradley Tower
KEN ANDERSON	Minneapolis Tower
KURT A. WILLIAMS	Houston Tower

GPO 914-340